

## NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

## TECHNICAL TRANSLATION F-21

## LUBRICATING OILS FOR AVIATION GAS TURBINES\*

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## Chapter I

## THE FUNCTION OF OILS AND OPERATING REQUIREMENTS IN GAS TURBINE ENGINES

The air breathing jet engines that include a compressor driven by a gas turbine, used in modern jet aircraft, are generally known as gas turbine engines (GTE). Two distinct types of GTE are designated as: turbojet engines (TJE) and turboprop engines (TPE).

Fig. 1 shows the basic diagrams of a TJE and a TPE, both with axial flow compressors. The turboprop engine, in addition to the components required by both engine types, has a propeller, driven by the engine shaft through a speed reducer. The speed reducer unit is an integral part of the engine in some designs, while in other TPE designs it is a distinct assembly that receives torque from the engine through a long shaft and shaft couplings.

The operating principle of the gas turbine engine may be summarized as follows: atmospheric air having passed through the intake section of the engine 1, enters the compressor 2, where it is compressed on the average 4 to 6 : 1 and experiences a resultant temperature rise of 200 to 300°. The compressed air flows continuously to the combustion chambers 3, where fuel is introduced through injectors. The gaseous combustion products, at a temperature of about 900°, pass through the turbine 4, thus rotating it, and then, after passing through the jet nozzle 5, are expelled at high velocity into the atmosphere.

The potential energy of the combustion products, acquired by them as a result of the initial compression of air in the compressor and the subsequent addition of heat in the combustion chamber, is partly converted to kinetic energy in the expansion through the turbine and is utilized for rotation of the turbine which drives the compressor and other components of the TJE. The rest of the potential energy is converted to kinetic energy in the jet nozzle, thus creating the thrust of the engine through reaction of the high velocity gas jet leaving the nozzle.

In the turboprop engine almost 90% of the potential energy of the combustion products is converted to kinetic energy during the expansion process through the turbine. The major part of the generated shaft horsepower is transmitted to the speed reducer 6, and is used to drive one or several propellers 7.

There are many design variations in the general class of propulsion power plants known as gas turbine engines. To show the location of the oil system and to introduce the operating requirements for oils in a GTE, an external view of a modern GTE is given in Fig. 2. The engine (Fig. 3) has an intake

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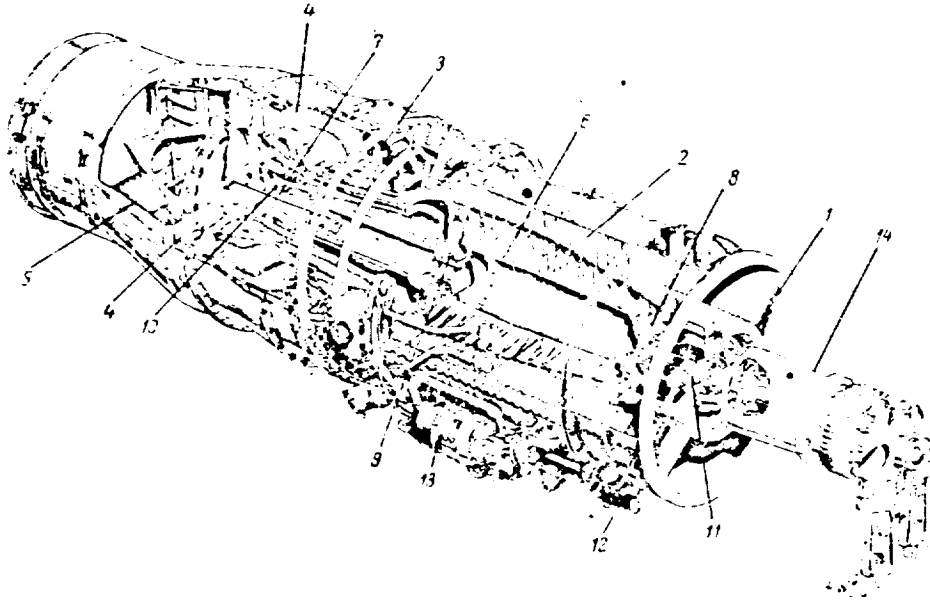


Fig. 3. Sectional view of a turbojet engine (left side view).

1 - Intake section of engine; 2 - 13 stage axial compressor; 3 - annular combustion chamber; 4 - two stage turbine; 5 - jet nozzle; 6 - compressor rotor shaft; 7 - turbine rotor shaft; 8 - twin row ball bearing at forward end of compressor rotor; 9 - roller bearing at aft end of compressor rotor; 10 - gas turbine roller bearing; 11 - gear transmissions to accessories' drives; 12 - left side drive box for accessories; 13 - fuel pump; 14 - engine starter with planetary speed reducer.

then at sonic velocity (1050 km/hr) at the same altitude, the temperature of the entering air increases to  $-13^{\circ}$ ; at a speed of 2150 km/hr, which is twice the speed of sound, the air temperature reaches  $+120^{\circ}$  and at three times the speed of sound (3200 km/hr) it reaches over  $300^{\circ}$ . In addition, the air temperature increases in the engine's compressor by an additional 200 to  $300^{\circ}$ ; as a result the temperature of the air leaving the compressor may be as high as  $400-500^{\circ}$ . Air heated to such high temperatures can not be used for the cooling of bearings and lubricating oil. For this reason, wide use has recently been made of fuel for oil cooling, by feeding the fuel through a fuel-oil heat exchanger before it enters the combustion chambers. This method of oil cooling has limits of application since at high velocities and during long flights

the fuel itself is heated in the aircraft's fuel tanks to critical temperature. There have been attempts at using the heat capacity of fuel for cooling of various parts of the engine, of electronic equipment, of air for cabin pressurization and of other units. All this leads to the unavoidability of future increases in bearing and lubricating oil temperatures.

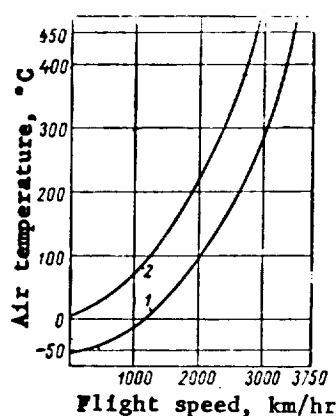


Fig. 4. Temperature of stagnated air as a function of airplane flight velocity.

1 - at flight altitudes of 11000 m and up; 2 - at sea level flight altitude.

At the same time the unsatisfactory high temperature oxidation stability of existing petroleum base oils limits allowable oil temperatures in the engine to the range of 130 to 150°. For this reason much effort has been devoted to attempts to improve petroleum oil stability and to the search for synthetic lubricating oils, that would be stable at temperatures of 250 to 400° /1, 2, 3, 4, 5/.

#### The GTE Lubricating System

Lubrication and cooling of rubbing parts in a GTE is generally accomplished by means of continuous circulation of oil through the engine. The pumping capacity required for this reaches considerable values in modern GTE (20-30 liters/min in TJE and 60-80 liters/min in TPE), and is provided by a special oil system whose essential elements are an oil tank and the system assembly consisting of oil line tubing, feed and scavenging pumps, filters, air separators, oil injectors, a radiator and regulating valves. The detail execution of individual oil systems differs with type and purpose of the engine, but the general principles of oil circulation and the design of oil system components are common to all. This makes possible the presentation of

the essentials of modern lubricating systems while discussing specifically one particular GTE /6, 7/.

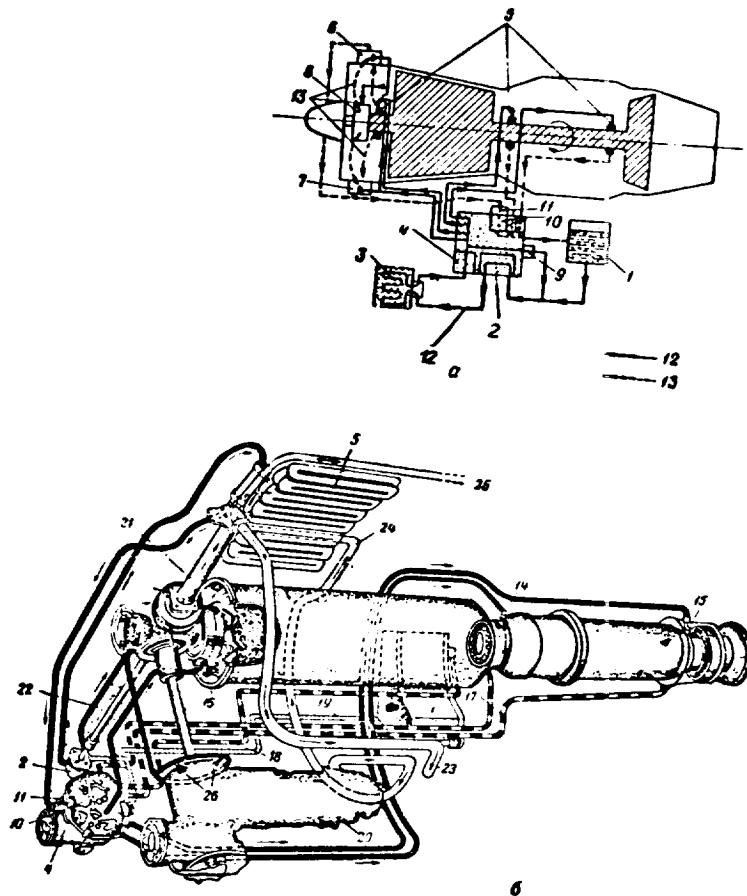


Fig. 5. Oil system of a modern GTE.

a - General diagram of the oil system; b - location of basic components of the oil system on the engine; 1 - oil tank; 2 - feed pump; 3 - fuel-oil heat exchanger; 4 - high pressure filter; 5 - oil injectors of the forward, middle and after bearings of the rotor shaft; 6 and 7 - accessory drive box; 8 - power take off box; 9 - pressure relief valve; 10 - scavenging pumps; 11 - low pressure filter; 12 - main feed line; 13 - scavenging and drain lines; 14, 15 and 16 - oil injectors at the bearings; 17 - oil lines from the bearings to scavenging pumps; 18 - oil line from scavenging pump to the oil tank; 19 - oil line feeding oil from the tank to the feed pump; 20 - fuel pump; 21 - centrifugal air separator; 22 - drain from the engine front end to the scavenging pumps; 23 - air breather pipe of the oil system; 24 - fuel feed line to the heat exchanger; 25 - fuel outlet line from the heat exchanger; 26 - oil injectors for the accessories.

Fig. 5a shows the basic operating diagram of a TJE, whose exterior view and sectional view are shown in Figs. 2 and 3. The diagram shows that the engine has a rather small (5 to 10 liters in volume) separate oil tank, 1. The oil is pumped out of the tank by pump 2, and then is fed under pressure through fuel-oil heat exchanger 3 and filter 4, to the oil injectors at the bearings 5, of the engine rotor shaft. The oil is also fed to the bearings and gears of the two accessory drive boxes 6 and 7, and to the bevel gears in power take off box 8. The quantity of oil fed to the various loops of the engine is determined by the areas of the injectors or special nozzles, and also by the pressure maintained in the system. The oil pressure is usually in the range of 2-4 kg/cm<sup>2</sup> and is controlled by a pressure relief valve 9, which bypasses oil back to the inlet side of the oil pump. The oil is scavenged from the bearings and drive boxes by three pumps 10, which are preceded by coarse wire mesh filters 11, protecting the pumps, and is then fed back to the tank. Fine filtration of the oil to remove foreign matter (dust, sand, metallic shavings, corrosion products, carbon particles, etc.) is usually accomplished by a cellular filter made of fine (0.05 mm) steel or brass wire. The oil pumps used in GTE are usually gear type or, more rarely, piston type pumps. The oil line tubing is made of steel or aluminum alloy with oil resistant rubber seal rings at the joints. The capacity of the scavenging pumps is 3 to 5 times greater than the capacity of the feed pumps.

Up to 30-60% by volume of air leaves the bearings and gear boxes. The high circulation rate of the oil leads to thorough mixing of the air and oil, and the intense scattering of oil at the bearings and gears leads to foaming of the oil. Conditions favorable to foam formation usually exist in a tank where the pressure is considerably lower than the pressure in the system and decreases sharply with increasing flight altitude. Intense foaming of the oil leads to ejection of foam through the breather, thus increasing oil losses and decreasing pump output. Temporary loss of oil flow to the points of friction, as a result of heavy ejection of foamed oil, may also occur. Some questions regarding the mechanism of foam formation are discussed in the work of G. G. Zuidema /8/. Intense foaming of the oil disrupts operation of the entire engine oil system. The foamed oil conducts heat poorly and possesses lowered heat capacity, which results in lowered heat removal from the engine parts. In addition the pressure of the foamed oil in the system drops sharply with increasing flight altitude, thus also disrupting normal lubrication of the engine.

To separate air from the oil various air separators are used. When circulation rates are high and high proportions of air are entrained in the oil, centrifugal air separators that lower the air content from 30-60% to 10-15% by volume, are used. The operating principle of these separators is the action of centrifugal forces when the oil-air emulsion is introduced into a fast rotating drum; these forces act to break up the emulsion. The oil is thrown to the wall and flows down to the oil pump housing, while the air is bled off to a breather from the central part of the separator. To better visualize the oil circulation in the engine, Fig. 5b shows a perspective diagram of the oil system of a modern TJE.

The oil systems of turbojet engines are somewhat simpler than the oil systems of aircraft piston engines, but certain characteristics of TJE oil systems create stringent operating requirements for the lubricating oil. Thus the absence of oil tanks in the aircraft leads to lowered total oil volumes

for many TJE (up to 15-30 liters in the highest power engines) while the circulation rates are high. The circulation rate in a TJE is 5-6 times higher than the rate in piston engines (PE). The oil in a TJE circulates up to 100 times per hour. All these factors as well as the elevated operating temperatures tend to intensify the extremely undesirable processes of decomposition and evaporation of the lubricating oil.

It is necessary to consider that the oil in a GTE comes into contact with various steels, aluminum alloys, brass, bronze and other metals that also influence changes in the oil during engine operation /1, 9/.

#### Operating Requirements for Oils in the Basic GTE Loops

All existing TJE and TPE utilize rolling contact bearings for the main supports of the rotor shaft - either ball or roller bearings. Attempts to use sliding contact bearings in the early GTE designs encountered great difficulties because of the need for a continuous oil film in the bearings during starting operation of the engine. In addition, the use of rolling contact bearings in the GTE led to several design and operating advantages. Among them are: a significantly lower coefficient of friction and therefore a relatively low engine starting torque requirement; lower sensitivity to temporary interruption of oil flow; the acceptability of lower viscosity oils; and others. Ball bearings are used for radial and axial loads, while roller bearings are used for radial loads only /10, 11/.

Radial loads on the engine rotor shaft bearings originate mainly from the weight of the rotor and from gyroscopic moments during aircraft maneuvers. The weight of modern TJE rotors is up to 400 kg and even higher. The bearing loads caused by gyroscopic moments can exceed rotor weight by a factor of ten.. Loads caused by unbalances in the rotor are usually small. Axial loads on the bearings of an engine having a symmetrical centrifugal compressor are not very great and consist mainly of the axial thrust of the turbine. In engines having a multistage axial compressor the axial loading is significant and reaches several tons. For assumption of the resulting compressor and turbine thrust loads, in this case two and sometimes three radial-thrust bearings are used.

In a TPE, significant axial loads generated by the propeller are transmitted to the speed reducer casing through the thrust bearing of the reducer shaft. Maximum thrusts generated here can reach 13-15 tons in a TPE of 10,000 hp. Study of the effect of the axial and radial loads on the bearing temperature shows that the temperature is primarily a function of the axial load. For rolling contact bearings the characteristic parameter is the linear velocity at the circle of centers of the balls. Maximum values of this linear velocity in a GTE are 50-70 m/sec. In practice it is more common to use the parameter " $dn$ ," where " $d$ " is the shaft diameter in mm, and " $n$ " is the number of rpm. Diameters of the shafts of modern TJE are in the range of 100-200 mm, while the speed of revolution is 5000-12000 rpm. Common values of the parameter " $dn$ " in the case of GTE bearings are  $0.9 \cdot 10^6$  -  $1.0 \cdot 10^6$ , and in some cases reach values near  $1.4 \cdot 10^6$ .

The linear velocity of the bearing versus bearing temperature is shown as a curve in Fig. 6. It is seen from Fig. 6 that the temperature increases



roughly linearly with increasing bearing speed, within the range of bearing operating speeds. If the bearing speed increases above the critical speed, indicated by the dashed line, the heat balance of the bearing is upset. This indicates the beginning of damage to the bearing. In modern high speed bearings the separators are destroyed first, since they are the weakest parts in the bearings.

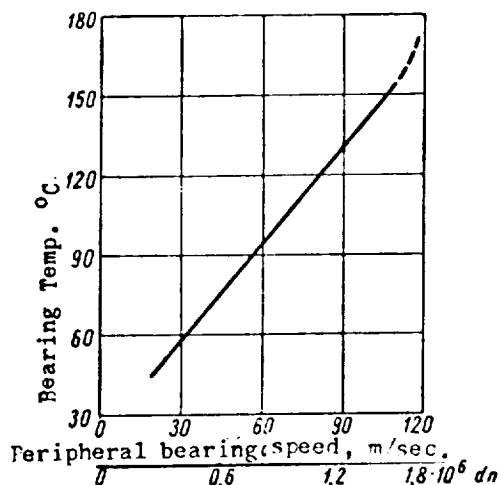


Fig. 6. Temperature of exterior race of a roller bearing as a function of linear velocity (internal bearing diameter 75 mm; radial load 730 kg; oil flow 3.6 kg/min; oil temperature at inlet, +38°).

Fig. 7 shows the types of bearings used in GTE. The basic material in these bearings is high carbon chrome-manganese steel. For bearings that are designed to operate at temperatures over 175°, the use of tool type steels has recently been initiated (these steels contain tungsten, vanadium and other additives) with tempering temperatures of 500-700°. Bearing separators are made of bronze or aluminum alloys. For high temperature bearings cast iron, titanium and other separators are being tried. Operating life of bearings is determined by test and depends on the magnitude, direction and nature of the imposed forces, on the speed of revolution, on the type of oil used and especially on the temperature of the bearing parts. The temperature environment of bearings is determined by the heat of friction, and to even a greater degree by heat transferred from various engine parts (the turbine, compressor, etc.).

Table 1 gives the temperatures of gas turbine engine bearings at the outside diameter, both during operation and after shut down.

It is seen in this table that the temperatures of bearings in the same engine differ widely; the forward bearing is at 50-80°, while the turbine bearing is at 125-175°. After engine shut down the flow of oil to the bear-

ings is halted while heat from the turbine disc and blades flows to the inner parts of the engine.

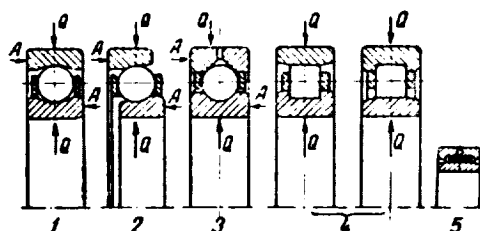


Fig. 7. Types of bearings used in gas turbine engines.

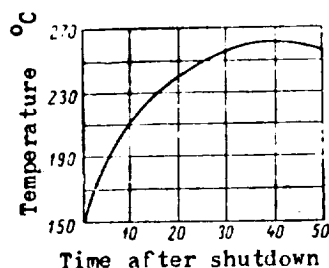
A - axial load; Q - radial load; 1 - single row ball bearing; 2 - single row radial-thrust bearing; 3 - ball bearing with split race; 4 - roller bearing; 5 - needle bearing.

The graph of bearing temperature change after engine shut down is shown in Fig. 8. It is seen that the bearing temperature continues to rise over a period of 40-50 min and reaches 260° in some engines. The center bearing temperature also rises, but less. Temperature increases of this magnitude in the turbine bearing lead to evaporation and oxidation of the oil on the surfaces of the bearing parts. In gas turbine engines of the near future, further increases in operating temperatures of the bearings are expected (up to 250-500°), and operating requirements on lubricants will correspondingly rise [12, 13].

Table 1

Temperatures of bearings of a modern gas turbine engine, during engine operation and after engine shut down

Location of friction	Bearing temperature, °C	
	During operation	After shut down
Speed reducer	80 - 110	80 - 110
Front bearing at compressor	50 - 80	50 - 80
Rear bearing at compressor	100 - 125	125 - 130
Turbine bearing	125 - 150	240 - 260



**Fig. 8.** Variation of outer race temperature of turbine bearing after engine shutdown.

The oil that is fed into the bearing performs the following functions:

a) it decreases sliding friction between the rolling members and the bearing races, between the rolling members and the separator, and also between the separator and the races; it also reduces the sliding friction that arises as a result of elastic deformations of the working surfaces (the rolling members and the grooves) under load;

b) it facilitates the equal distribution of heat over all parts of the bearing and removes heat;

c) it protects the polished surfaces of the rolling members and the race grooves from corrosion, and also gives corrosion protection to the other surfaces in the bearing;

d) it fills the gaps between bearing parts and thus ensures greater elasticity of load transfer between them.

The initial period and the first years of development of gas turbine engines were characterized by the existence of contradictory views on lubrication of high speed bearings. Some designers thought that high speed bearings should be lubricated and cooled by a mixture of air and oil and not by oil alone. This was based on the fact that little oil is required for lubrication of a rolling contact bearing and that cooling of the bearing can not be increased by increasing the flow of oil, since agitation of the increased quantity of oil simply increases its temperature. Thus the bearings of the first gas turbine engines were cooled with oil, and mixtures of air and oil. In some cases the forward bearings and the accessory drives were lubricated with oil while the rear bearings of the same engine were fed mixed air and oil. In these cases the air and oil mixture was usually expelled to the atmosphere or was burned in the engine ducts after lubricating and cooling the bearings.

Further experiments with bearings and operating experience with full scale engines indicated that a mixture of air and oil does not insure proper cooling of the bearings. Added to this inadequacy were the fact that greater quantities of oil were used in this system than in an oil circulation system,

and the need for special filtration of the air fed to the bearings. Therefore it became common to use only oil for bearing lubrication. However the possibility of using air-oil mixtures in certain engines of the future should not be excluded.

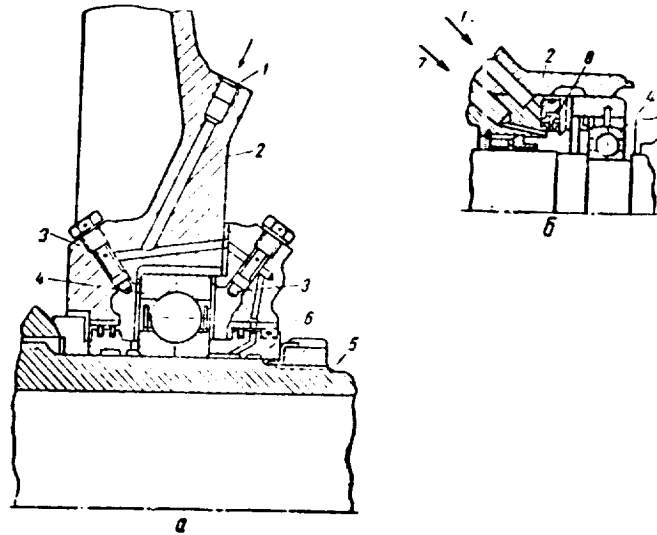


Fig. 9. Lubrication of ball bearings.

a - oil only; b - air-oil mixture; 1 - oil inlet; 2 - engine frame; 3 - oil injectors; 4 - ball bearing; 5 - engine shaft; 6 - ring oil seal; 7 - air inlet; 8 - calibrated aperture.

Fig. 9 shows examples of ball bearing lubrication with oil and with air-oil mixture. It is seen in Fig. 9a that the oil is fed to the bearing through injectors that are so installed that the jet of oil is directed into the gap between the separator and the inner bearing race. A small part of the oil goes inside the bearing and lubricates its rolling and sliding parts, while the major part of the oil bathes the surfaces of the separator and races, removing heat from them. The more common method is to feed the oil to the bearing in a solid stream that comes from an injector through a contracting nozzle. The quantity of oil delivered to the bearing is determined in this case by the diameter of the nozzle, by the oil pressure and the oil viscosity. In modern gas turbine engines the flow of oil through each bearing is between 100 and 300 liters per hour and sometimes even more.

In a TPE the basic thrust is generated by one or two contrarotating propellers, which receive their torque from the gas turbine. The speed of rotation of modern TPE lies in the range of 8000 to 14000 rpm. Pusher or tractor propellers however develop their greatest efficiency at 900-1100 rpm, that is, at speeds that are considerably below the turbine speed. The indicated speed reduction is usually accomplished in a TPE by means of a geared speed reducer having a speed ratio of about 10 : 1. The tremendous horsepowers transmitted by the reducer, reaching 15000-20000 hp in some cases, the

requirement for low weight and compact design, all make for a complex kinematic system and for extremely high pressures in some parts and elements.

The gears and shafts of the speed reducer are made of high strength steels. Dependable speed reducer operation requires the use of oils that have high lubricity and the required viscosity.

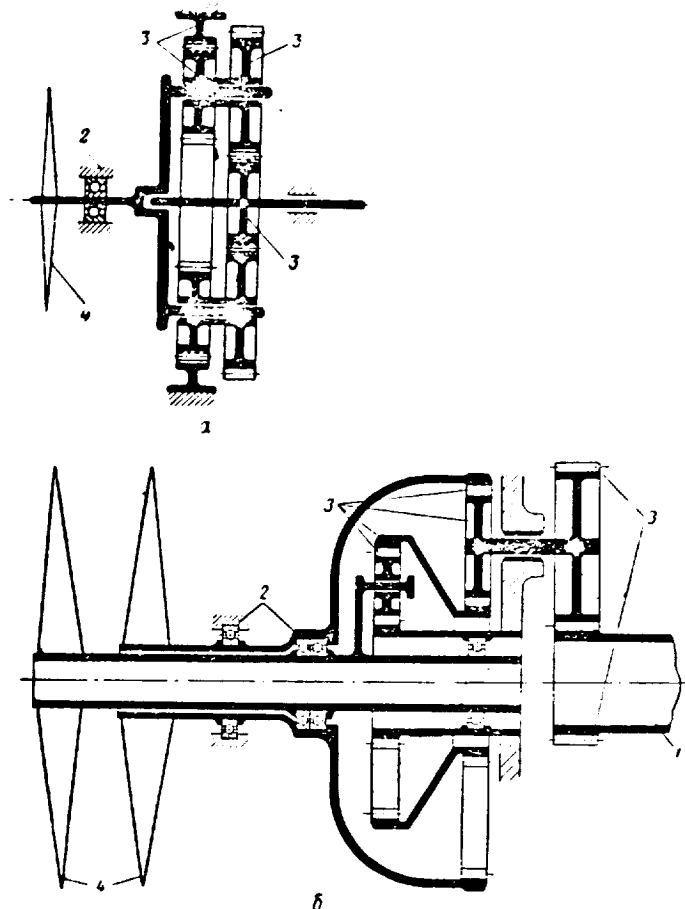


Fig. 10. Diagram of TPE speed reducer.

a - planetary speed reducer driving one propeller; b - combination speed reducer transmitting power to two coaxial propellers; 1 - engine shaft; 2 - bearings that take the thrust force of the propellers; 3 - gears of the speed reducer; 4 - propeller.

Fig. 10a shows the diagram of a planetary speed reducer in a TPE having one propeller. In high power TPE it is more common to use combination speed reducers for driving two coaxial propellers that rotate in opposite directions. The diagram of one such speed reducer is shown in Fig. 10 b.

The gears in a speed reducer may have spur teeth, helical teeth, herringbone or bevel teeth. The contact pressures in the gear teeth of modern TPE reach compression values of 10000-15000 kg/cm<sup>2</sup> and higher. However the maximum surface shearing forces induced by contact pressures are more dangerous for gear teeth since they lead to elevation of working surface temperatures at the moment of tooth engagement up to values at which the oil could be squeezed out of the contact area and thus produce seizing of the gear tooth surfaces. It has been established that the elevation of temperature leading to seizing of working surfaces, usually lies in the range of 200-250° and does not exceed 300°. Surface shearing stresses in the gear teeth of modern TPE lie in the range of 3500-5800 kg/cm<sup>2</sup> /1/.

During engine operation the speed reducer gearing is lubricated and cooled by the same oil that is used in the engine. The oil is fed by means of a special pump through channels in the reducer casing, through calibrated apertures, as shown in Fig. 11. Usually the oil stream is directed at the smaller gear at its disengagement side.

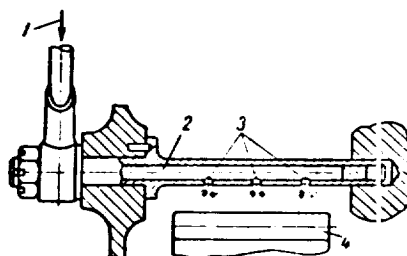


Fig. 11. Oil delivery to the gear teeth of a TPE speed reducer.

1 - oil inlet; 2 - oil channel; 3 - calibrated apertures; 4 - gear tooth.

Special attention is devoted to the lubrication of the ball bearings that take the propellers' thrust load. The friction present in the action of the speed reducer's gear teeth and the resultant rise in oil temperature necessitates high oil flow rates through the reducer, these rates equaling about 10 liters/min for each 1000 hp of the engine.

Within the reducer the oil comes in contact principally with the alloy steels of the gears, bearings, shafts and so forth, as well as with the aluminum alloy of the reducer casing /1, 14/.

Modern aviation gas turbine engines are equipped with a large number of accessories that are essential for normal operation. Some of these are the fuel and oil pumps, speed regulator, starting equipment, fuel pump for high level engine operation, and others. In addition many other accessories operate through drives from the engine, for instance, the electrical generator, the hydraulic pumps, the air-vacuum pump, the air compressor, etc. Some of these accessories are located directly on the engine while others are installed separately and are linked to the engine by shafting. All this requires a special system of drives, which usually include bevel and spur

gears and shafts.

The general diagram of the drive system for accessories of a TJE is shown in Fig. 12. The total power transmitted through this system is relatively small and lies in the range of 200-500 hp. However the requirement for minimum dimensions and weights leads to the condition of highly loaded components in the accessory drive systems of modern gas turbine engines, particularly of TJE, and these components require definite attention for the solution of their lubrication problems.

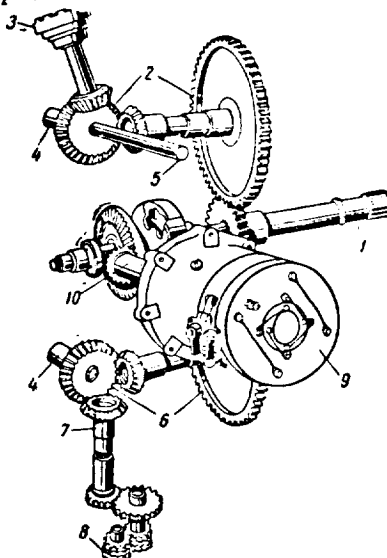


Fig. 12. General diagram of drive system for accessories of a turbojet engine.

1 - main shaft transmitting torque from the engine; 2 - gears of airplane accessories drive box; 3 - shaft of airplane accessories drive box; 4 - drives to fuel pumps; 5 - tachometer generator drive; 6 - gears of the oil and fuel pump drive; 7 - drive shaft for oil pumps; 8 - oil pumps; 9 - engine's electric starter; 10 - drive from starter to the engine.

Modern GTE include various devices that control operating modes of the engines under various conditions of operation. Among them are two mechanisms of interest, whose proper operation depends to a significant degree upon the lubricating oil used. These components regulate fuel delivery to the combustion chambers and the pitch of the propeller blades. Oil in these components acts as the working fluid in hydraulic regulators of the valve type and in servomechanisms.

The oil must ensure smooth and uninterrupted operation of the valve which varies the quantity of fuel fed to the engine, and the position of the servo piston whose thrust is transmitted to the propeller pitch change mechanism. In these regulators the required oil film is easily maintained since there are no high temperatures and no high loads. However the oil must ensure operation of the regulators at low temperatures during engine start up in winter or during flight at high altitudes. Any large increase in oil

viscosity leads to decreased speed of regulation, to oscillations in the engine speed, and produces a decrease in the rate of propeller pitch change.



## Chapter II

### REQUIREMENTS FOR GAS TURBINE ENGINE OILS

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The operating conditions for lubricating oils in various loops and components of GTE determine a series of typical requirements for the oils. The lubricating oil must ensure dependable operation of the entire engine, and therefore must satisfy an entire complex of requirements relating to the lubrication of gears and bearings and the operation of regulators, servo mechanisms and other components under various conditions. It is evident that the production of an oil that would fully satisfy all these requirements is extremely difficult. Therefore in developing and selection of GTE oils every attempt is made to satisfy to the maximum extent possible the basic operating requirements.

The following must be included in the more important requirements for GTE oils:

- 1) Oxidation stability at high temperature;
- 2) Good flow characteristics at low temperatures;
- 3) Satisfactory wear resistance properties.

In addition the lubricating oil must be adequate in terms of evaporation rate, anticorrosion properties, foaming, hydrolysis resistance, biological toxicity and effects on rubber and other materials.

#### High Temperature Oxidation Stability

The hottest parts of a GTE that are contacted by lubricating oil are the main shaft bearings and particularly the gas turbine bearings. The operating temperatures of turbine bearings in presently operating GTE reach 175°, and after engine shut down they reach up to 260-270°. Recent literature /15, 16, 17/ indicates that there will be further increases in GTE bearing temperatures.

The maximum operating temperature of the outer race of the bearings in designs under development may reach 250°, and 350° after engine shut down. For feasible engines in high speed aviation much higher bearing temperatures are being considered: near 400° during engine operation and 550° after shut down. For such conditions it is quite difficult to formulate definite requirements for lubricating materials, but doubtless these materials will have to be stable at operating temperatures and will have to ensure complete lubrication of parts in friction. The oils must be sufficiently precipitation resistant and lacquer formation resistant at high temperatures, and must not corrode metals. The time of contact between engine parts and oil must be taken into account when

the parts are heated to the above indicated high temperatures, as well as the degree of air entrainment in the oil, which plays a large role in oil decomposition processes.

The high bearing operating temperatures in a gas turbine, as well as the presence in a GTE of various cavities in which oil is mixed with air at considerable temperatures, demands definite concern for the flash temperature and autoignition temperature of the oil. Simultaneously the possibility of hot gases penetrating through the bearing seals must be considered. The flash temperature of the oils must be over 200° since ignition has been observed at lower temperatures. Meaningful requirements for limiting values of flash temperature and autoignition of oils for feasible GTE can be established only through experimental methods.

#### Flow Characteristics at Low Temperatures

The oil must insure the possibility of starting the engine on the ground and in the air even under the lowest temperatures encountered, and this depends on the viscosity properties and on the jelling temperature of the oil as well as on the design details of the engine. In most cases it is considered sufficient if the jelling temperature is not over -60°, although the ambient air temperature sometimes drops to even lower values [18, 19].

The possibility of preliminary heating or dilution of the oil before GTE start up is in most cases excluded. The former is unacceptable in most cases because of the difficulty of servicing the aircraft in winter time. The dilution of oils with fuel, widely used in piston engines, proved to be extremely undesirable for GTE and completely unacceptable in some cases because of the very slow rate of evaporation of the fuels used in these engines, which resulted in excessively long periods of operation at low viscosities and at concomitant low flash temperatures of the lubricant mixture. The use of special volatile solvents for dilution of the oil, results in a high fire hazard in addition to the added complexity and added weight of the oil system. The combination of fire hazard requirements plus the low temperature requirements in aviation GTE make a particularly difficult set of requirements for these oils.

Both operating experience and the results of special tests with GTE have shown that the temperature limit for cold start depends upon the flow ability of the oil and upon the pressure that can be generated throughout the entire engine oil system. The flow ability of the oil and its pressure depend primarily upon the oil viscosity at low temperatures and the oil's average air content. It was established by means of tests on engines using various oils that the maximum allowable oil viscosity is about 4000 centistokes when the oil is not saturated with air [19]. It should be noted that the flow properties of the oil at low temperatures depend heavily upon the design of the engine, the location of the oil tank, the oil pump and other factors. For this reason somewhat different low temperature specifications are made for oils in various engines, the basic specification being the maximum allowable oil viscosity, which is 3000 centistokes for TPE and for some types of TJE about 10000 centistokes.

### Wear Resistance Properties of Oils

Lubricating oils must protect bearings and gear trains from high wear rates and must prevent the seizing of rubbing parts. These capabilities are determined by oil viscosity at operating temperatures of rubbing elements and by the lubricity of the oil.

Higher requirements are made on the viscosity and lubricity of oils to be used in TPE. For normal operation of most TPE, oils having viscosities in the range of 15-20 centistokes at 100° are desired. The use of less viscous oils leads to increased form error in the working surfaces of the gear teeth and this eventually leads to complete failure of the speed reducer.

In the opinion of some specialists, when low viscosity oils are used in gear trains, the oil penetrates into microcracks in the metal and destroys the tooth material, acting in the manner of a hydraulic wedge. There is also some speculation that the total pressure on a gear tooth surface is really concentrated over a smaller surface area than when proper viscosity oils are used, and in consequence bearing stresses on the material increase. These effects may be observed also in rolling contact bearings, where they reduce bearing life. Small pits are produced in the surfaces of the bearing races and of the rolling members and this effect, called pitting, is the result of fatigue failure in the surface material. Oil of low viscosity penetrates into the pits, and by enlarging the breaks in the surface, destroys the working surface. The formation of pits can be prevented by using more viscous oil /20/.

In the case of turbojet engines the viscosity requirements are less stringent: the oil viscosity in these engines must be 6-8 centistokes at 50° (and about 3 centistokes at 100°). Good lubricity reduces the friction between rubbing parts, strengthens the oil film, prevents seizing of rubbing parts and facilitates the operation of bearings with minimum wear. The role of lubricity is particularly great in those cases where the rubbing parts are not completely separated by a film of oil or where conditions are not right for the formation of a liquid oil film and the lubricant's action is no longer determined by its viscosity. The lubricity of an oil is the result of formation on the metallic surfaces of boundary phases with correct orientation of the molecules.

High molecular orientation ability is possessed by surface active polar molecular chains that contain the groups CO, COH, COOH, S and others. In petroleum oils polarity is possessed by naphtenic and carboxylic acids, by resins, by sulfur compounds and other compounds /8, 21/.

High wear rates in rubbing surfaces of GTE are undesirable since they lead to enlargement of gaps between the parts, to misalignment of shaft axes, etc. and thereby curtail the operating life of the parts and components. Thus in many cases highly active sulfide, phosphide and other additives having well defined polar chains, are mixed into aircraft lubricating oils.

It is desirable that synthetic oils for GTE have higher anti-wear properties than the ordinary mineral oils that are used at present in operating engines /19, 22/.

### Vaporization, Corrosion Properties, Foaming and Other Requirements for Oils

The vaporization, corrosiveness, foaming properties of oils and their resistance to hydrolysis are important in the development of oils for GTE.

An elevated vaporization rate leads to large oil consumption rates in operation, and may lead to complete loss of oil from the turbine bearings after engine shut down. In addition the high evaporation rate of the volatile fractions leads to a gradual change in oil composition and properties and primarily to an undesirable increase in the oil viscosity at lower temperature. Thus in selecting oils for GTE duty their volatility is rigidly specified by imposing limits on the loss of oil during heating over a specified time or on the change in viscosity at low temperature following a period of heating.

In some oil specifications it is stipulated that weight losses of oil during heating for 6.5 hours at a temperature of 175° must not exceed 3-5%; and other specifications stipulate that the increase in oil viscosity at low temperatures following elevated temperature tests must not exceed 10-20%.

Since the vaporization rate of oils is to a considerable extent connected with the boiling temperature of the various fractions or components, it is usually specified that the initial boiling temperature be a minimum of 50° above maximum operating temperature. No limits are usually specified for the saturation vapor pressure of oils at various temperatures but in the future this will have to be considered as synthetic lubricating oils are developed.

The oils must not only be noncorrosive to the engine metals but should also protect the metals during engine shut down periods.

Various parts and components of the oil system incorporate a variety of metals (steel, aluminum alloys, brass, bronze, etc.). These metals differ sharply in corrosion resistance.

At elevated temperatures conditions favorable to corrosion are created. The corrosiveness of lubricating oils is essentially dependent on the composition and properties of the decomposition products of the oils. The development of corrosion is significantly affected by the degree of removal from the oil of volatile oxidation products. At high speeds of rotation of the shaft of a jet engine even insignificant corrosion defects on the surfaces of rolling bearing members may produce serious damage and even destruction of the bearing /8/.

Earlier the conditions leading to foaming were discussed and the detrimental effects of foaming on lubrication system operation were pointed out. The foaming of an oil depends on its nature. It has been noted that some oil components and additives that are used to improve stability and other properties, may increase the foaming tendency of the oil. This tendency may be inhibited by addition of anti-foaming agents to the oil /8/. Resistance to foaming is a highly desirable property for GTE. Thus the evaluation of oils for foaming properties is of high practical significance.

The results of research on synthetic oils for GTE have shown the

importance of thorough investigation of the effect of water on the oil. The possibility of water penetration into the lubricating system of an operating GTE must not be overlooked. When petroleum oils are used, this does not have any practical effect on the oil quality. Some synthetic ester base oils decompose when in contact with water and liberate precipitates and other harmful products.

The significance of oil toxicity is connected with the fact that in most jet aircraft the cabin is pressurized by bleeding air from the engine compressor. Small quantities of oil can enter the air ducts and vapors or oil fog can penetrate into the aircraft cabin. Therefore in developing new oils and in selecting additives for them it is important that no toxic elements be incorporated into the new oils.

In conclusion it should be noted that there is yet another series of requirements that are not decisive in development of new oils but still are to be considered before making a final selection. These requirements relate to the action of oils on various materials that are used in GTE (gaskets, finishes, etc). In addition the questions of raw material availability and economics of production of new oils are significant in the selection of a new lubricant.

### Chapter III

#### PETROLEUM OILS

The principal lubricants currently used in gas turbine engines are petroleum oils. In the case of turbojet engines, these are low-viscosity petroleum oils obtained from butyric, paraffinless, low-tar petroleum /23, 24, 25/. The most widespread types of turbojet oils have a viscosity at 100° ranging from 2.5 to 3.5 centistokes. For turboprop engines, on the other hand, the lubricants required are, as is known, oils ensuring high wear resistance. The oils used in the second case, therefore, normally are the more viscous petroleum oils with viscosities at 100° of approximately 9 to 20 centistokes.

Table 2 lists the physical and chemical properties of petroleum oils used in nationally manufactured gas turbine engines either solely or as components./26, 27, 28/.

MK-8 oil is one of the basic types of light petroleum oil for turbojet engines. It is obtained by deep refining of the distillates of Balakhan, Dossor and other high grade petroleums. Compared to the oils listed in Table 2, MK-8 oil has a lower solidification point and is subject to more favorable temperature-viscosity variations at low temperatures. This type of oil fully ensures normal operation of the bearings and other frictional parts of turbojet engines working at moderate temperatures. The important drawbacks of MK-8 and other light petroleum oils of similar fractional composition are their very high volatility and low oxidation resistance at high temperatures.

The closest to MK-8 oil in terms of viscosity and other properties is transformer oil, which differs from it in having a higher solidification point. There is information regarding the use in gas turbine engines operating at high temperatures, of turbine oil /27/ with better lubricating properties and substantially lower volatility.

Turbine oil is made from carefully selected crude processed on the basis of effective refining methods. The viscosity of turbine oil at 50° is considerably higher than that of MK-8 and transformer oil, while its acid number is lower. This type of oil must meet very stringent requirements for oxidation resistance. Turbine oil is inferior to MK-8 as regards the solidification point and has less favorable viscosity characteristics at low temperatures.

The wear resistance properties of low viscosity petroleum oils may be improved by mixture with higher-viscosity oils. For this purpose, use is made of the highly refined residual lubricants utilized in aircraft piston engines. These include the selectively refined MS-20 oil given in Table 2,

which has good oxidation resistance and low corrosion activity.

**Table 2**  
**Physical and Chemical Properties of Petroleum Oils**

Indicators	MK-8	Transformer oil	Turbine oil	MS-20
Viscosity, in centistokes, at temperatures in °C:				
100 . . . . .	-	-	-	20
50, not less than. . . . .	8.3	9.6	20-23	-
20, not less than. . . . .	30.0	30.30	-	-
Viscosity ratio:				
$\frac{v_{-20}}{v_{50}}$ not more than . . . . .	60	-	-	-
$\frac{v_{50}}{v_{100}}$ not more than . . . . .	-	-	-	7.85
Acid number in mg of KOH, not more than	0.04	0.05	0.02	0.05
Stability (according to the All-Union Heat Engineering Institute method)				
residue after oxidation, in %age, not more than . . . . .	0.1	0.1	0.1	-
acid number after oxidation, in mg KOH, not more than. . . . .	0.35	0.35	0.35	-
Coking property, in %, not more than	-	-	-	0.3
Ash content, in %, not more than. .	0.005	0.005	0.005	0.003
Sulfur, in %, not more than . . . . .	0.14	-	-	-
Flash point, in °C,				
in closed crucible, not lower than	135	135	-	225
in open crucible, not lower than. .	-	-	180	-
Solidification point, in °C,				
not higher than . . . . .	-55	-45	-15	-18
Aniline point, in °C, not lower than .	79	-	-	-
Corrosiveness (according to Pinkievich) in g/sq. m, not more than . .				
	-	-	-	45
Density $\rho_{4^{20}}$ not more than. . . .	0.885	-	-	0.895

Like all aviation oils /29/, MS-20 has a high solidification point: -18°, and very high viscosity at low temperatures. For instance, the viscosity of MS-20 at -10° is in the neighborhood of 40,000 centistokes, whereas MK-8, even at -30°, has a viscosity of only 3,000 centistokes. It is natural that the addition of highly viscous aviation oils to light distillate oils should substantially lower their fluidity at low temperatures. Also, oils for gas turbine engines obtained by mixing have poor starting properties

when the engine is started cold.

During the initial phase in the development of jet aviation, the requirements to be met by lubricating oils were not very high and light petroleum oils fully satisfied the operating needs of gas turbine engines of all types. According to Hunt /18/, the chemical composition and properties of oils during tests on aircraft in operating conditions altered little or not at all. Subsequently, as the power output of engines increased and as aircraft operating conditions changed, owing mainly to increases in speed and flight altitude, particularly in military aviation, the requirements for lubricating oils became more and more stringent.

Quick starting of the engines and the reliability of operation of the regulating mechanisms at low temperatures are a function of the improvement of viscosity-temperature characteristics of oils.

Temperature rises in frictional couplings and the increase in flight altitude are making it necessary to increase the stability of oils, and to lower their volatility. The wear resistance offered by oils, particularly in the case of turboprop engines, requires increasing attention.

The search for ways of improving the operating qualities of lubricating oils involves examination of the physical and chemical properties and composition of petroleum oils, as well as the study of the relationships between oil structure and behavior in the engine. It is known that petroleum oils are complex mixtures consisting basically of paraffin, naphtha and aromatic hydrocarbons. In addition to these, petroleum oils also contain compounds of oxygen, sulfur and other substances in small quantities. /25,30/.

The chemical composition of an oil and the structure of the compounds contained in it will govern the physical and chemical properties of the oil as well as its behavior in operation. Even minor variations in chemical composition will have a substantial effect upon their viscosity characteristics, stability and other properties.

L. I. Saranchuk and N. F. Ronzhina have investigated the viscosity at low temperatures of two gas turbine engine oils having similar indices except for the solidification point. Oil A was obtained from Balakhan petroleum, whereas oil B was derived from a mixture of several types of petroleum from the Baku region. Some of the physical and chemical indices of these oils and their viscosities at low temperatures are given in Table 3.

It may be seen from Table 3 that down to  $-10^{\circ}$  the viscosity of both oils is approximately the same and that at lower temperatures, the viscosity of oil B increases much more sharply than that of oil A. The viscosity of some of the samples from mixed petroleum at  $-40^{\circ}$  was as high as 13,000 centistokes. The poor viscosity characteristics of oil B at low temperatures are explained by its less favorable hydrocarbon content. Apparently the oil obtained from mixed petroleum contains cyclic hydrocarbons with shorter side paraffin chains.

As light oils heat up when the engine is operating, they undergo intense volatilization, particularly on high altitude flights. As a result of this, the lightest fractions are eliminated, causing an increase in the viscosity of



the oils and therefore a deterioration of their starting properties at low temperatures.

Table 3

Viscosity of Turbojet Engine Lubricating Oils Derived From  
Different Types of Petroleum, at Low Temperatures

Indicators	Oil A, Balakhan petroleum	Oil B, derived from a mixture of Baku petroleums
Viscosity, in centistokes, at temperatures in °C:		
50 . . . . .	8.2	8.2
20 . . . . .	27.6	27.5
-10 . . . . .	210.8	210.7
-20 . . . . .	585.8	666.6
-30 . . . . .	1760	2041
-40 . . . . .	6300	9464
Solidification point, °C. . . . .	-53	-44
Acid number, in mg of KOH. . . . .	0.02	0.02
Flash point, °C. . . . .	146	146

Research conducted by these same authors to determine the effect of oil evaporation on increases in viscosity has shown that the viscosity of oils at low temperatures, after the elimination of light fractions, is very substantially increased. Oils were evaporated at ambient air pressure, in flasks, at temperatures of 150 and 175°. 100 g of oil were poured into the flask and air was made to pass through at the rate of 1.2 liters per minute. The vapors of volatilized oil were collected in a receptacle. A description of the method of determining the volatility of the oil is given in the last section of the book.

From the data of Table 4 it will be seen that both oils volatilize very readily. As a result of evaporation for 5 hours at 175°, the light fraction losses in oil B were 5% greater than in oil A.

Variations in oil viscosities are shown in Table 5. The viscosity of oil A at -40°, after evaporation for 5 hours at 175°, increased about 2.6 times, whereas the viscosity of oil B, under the same conditions, increased 2.2 times. For the purpose of comparison, data are also given on the viscosity of oil B at +50° and -40° collected from the oil system of a turbojet aircraft after 25 hours' operation at comparatively low temperatures.

The increase in viscosity at 50° after the engine has been operating for 25 hours is only slightly greater than the variation in viscosity after the

oil was evaporated for 5 hours in laboratory conditions. At  $-40^{\circ}$ , the viscosity of the same oil altered quite substantially. After 25 hours' operation, the viscosity of the oil at  $-40^{\circ}$  increased from 9464 to 28,200 centistokes, representing an increase of almost three times.

Table 4

Volatility of Turbojet Engine Oils from Different Petroleums

Oil	Evaporation time, hours	Volatility, weight %, at temperatures of:	
		145°	175°
Balakhan petroleum oil A	1	1.56	4.62
	2	2.84	7.82
	3	4.71	13.99
	4	5.86	20.98
	5	7.12	23.66
Mixture of Baku petroleum oil B	1	1.89	8.99
	2	4.25	15.74
	3	6.44	21.72
	4	8.55	28.09
	5	9.67	28.62

Fresh oil A which has better viscosity at low temperatures makes it possible to start the engine without warming up only down to  $-35^{\circ}$ , whereas aircraft operation makes it desirable for the oil to ensure engine starting at  $-50$  and  $-60^{\circ}$ .

A high increase in the viscosity of the oil during engine operation introduces a marked deterioration of its low temperature starting properties which are not always operationally satisfactory even in the case of fresh oil.

It will be seen from the data in Table 6 that oil evaporation by the passage of air is accompanied by a substantial increase in the acid number of the oil, particularly at  $175^{\circ}$ . This shows that the oils become oxidized.

Oil B turned out to be less stable. Its acid number increases more intensively owing to the fact that it contains hydrocarbons with a lower oxidation resistance /31/.

The oil's acid number likewise increased under operating conditions. The following are acid number values of samples of oil B taken from aircraft:

	<u>Acid number, mg of KOH</u>
Fresh oil	0.02
After 42 hrs 52 min of engine operation	0.12
" 57 hrs 14 min " " "	0.15
" 100 hrs 02 min " " "	0.18

Table 5

**Viscosity of Oils of Different Petroleum  
After Evaporation for 5 Hours at 175°**

Oil	Viscosity in centistokes at temperatures of:		
	50°	-30°	-40°
<b>A</b>			
Initially . . . . .	8.2	1760	6 300
After 23.7% evaporation, by weight, for 5 hours . . . . .	10.4	3280	16 704
<b>B</b>			
Initially . . . . .	8.2	2041	9 464
After 28.6% evaporation, by weight, for 5 hours . . . . .	11.1	3820	21 259
After 25 hours engine operation . . .	11.9	-	28 200

Table 6

**Increase in Acid Number During Evaporation**

Oil	Evaporation time, hours	Oil acid number, in mg of KOH, after evaporation, at temperatures of:	
		145°	175°
A (acid number: 0.020 mg of KOH)	1	0.022	0.039
	3	0.030	0.075
	5	0.033	0.161
B (acid number: 0.021 mg of KOH)	1	0.036	0.045
	3	0.055	0.083
	5	0.065	0.181

After 100 hours of engine operation, the acid number of the oil increased by a factor of 9. This agrees with the data obtained when the oil was tested in the laboratory for 5 hours at 175°.

Increasing attention has been devoted recently to lubricating oil frothing. It has been demonstrated earlier that oils in the engine oil system become saturated with large amounts of air. When the aircraft rises to a high altitude and is in a rarified atmosphere, this air is expelled from the oil and forms a froth.

Research work by L. I. Saranchuk and N. F. Ronzhina on the forthring of oils derived from Balakhan petroleum and petroleum mixtures has shown that

oil A obtained from a single petroleum has a somewhat higher tendency to froth than oil B from the Baku petroleums. Oil frothing is determined by the L. V. Zhirnova method. The results obtained are given in Table 7.

Table 7

Oil Frothing Under Laboratory Conditions

Oil	Residual pressure at time of frothing, mm Hg	Altitude corresponding to instrument pressure, km	Oil temp- erature, °C	Frothing coefficient
A from Balakhan petro- leum	198	10	100	1.5
	90	15	200	1.1
	90	15	100	1.8
			200	1.5
	41	20	100	2.2
			200	1.6
B from Baku petroleums	198	10	100	1.1
			200	1.0
	90	15	100	1.2
			200	1.0

The frothing coefficient of oil is the ratio of the height of a column of froth formed in the instrument cylinder to the height of the oil in the cylinder before frothing. As may be seen, increases in the rarefaction of the air in the cylinder at the time when froth is being formed will lead to more intensified frothing of the oil.

Increases in oil temperature will decrease the amount of froth produced, this being primarily dependent upon a sharp drop in the viscosity of the oil. A rise in temperature will also lower the stability of the froth, which is determined by the duration of the froth. If at 100° froth lasts 20 to 25 seconds, at 200° it may last 1 to 5 seconds.

The chemical processes taking place in the oil during engine operation result in the formation of decomposition products, some of which are insoluble in the oil. Oxidation plays a dominant part in these processes. The trend of the reactions, their depth and the nature of the resulting products depend upon the chemical characteristics of the oil, the structure of the compounds of which it consists, their number and numerous other factors affecting the oil. Chief among these are: temperature, pressure, the catalytic effect of metals and the oil's decomposition products.

Various types of organic acids, hydroxy acids, ethers, resins, soaps of naphthenic and other acids, asphaltenes, carbenes and many other compounds are formed in the oil. In the course of operation, the oil acquires new properties which will depend upon the amount and content of the decomposition products. The quality of the oil in such circumstances usually

deteriorates. Many of the products of decomposition are harmful to the bearings and other engine parts.

The formation of acids and other substances in the oil may result in the corrosion of metal parts. The extent of corrosion depends essentially upon the nature of the acids and the metals' ability to resist corrosion. Those which attack metals most strongly are hydroxycarboxylic and low molecular weight fatty acids. Peroxydes likewise play an important part in corrosion.

In the engine, the oil comes in contact with various metals (steel, duralumin, brass, etc.) with widely differing corrosion resistance. Temperature and other conditions prevailing in various parts of the oil system have a great effect upon the development of corrosion. These conditions include the degree to which volatile decomposition products have been eliminated from the oil, the load on the working parts, the presence of air and other factors. Petroleum oils without any admixtures used in gas turbine engines operated at moderate temperatures are sufficiently inert in regard to metal corrosion. High temperatures favor corrosion. In selecting new oils for gas turbine engines, particularly those operating at high temperatures, it is essential to verify experimentally the corrosive activity of lubricating oils on the metal parts of the oil system in simulated operating conditions.

The engine may be greatly damaged by solid hydrocarbon decomposition products of petroleum oils.

Two types of hydrocarbons are formed in gas turbine engines: lacquer films and sediments. There is normally no deposition of hydrocarbons in the form of scaling in the oil systems of gas turbine engines.

Lacquer films or lacquers are deposited in gas turbine engines in the form of solid lacquer-like layers on the heated metal surfaces of the oil system and components of roller bearings. They may range in color from light yellow to brown and black. Sediments are the insoluble, brown or nearly black decomposition products that settle on various parts of the engine's oil system. Sediments occur in the form of grease clots or resin deposits.

The formation of hydrocarbon and resin deposits in gas turbine engines and the degree to which their composition and properties depend on the oil and the operating conditions of the engine have still been but little explored, but it may be assumed that the process of their formation resembles similar phenomena in piston engines. Lacquer films are formed as a result of the action of high temperature and oxygen in the air upon a thin layer of oil. An important role in this connection is played by the catalytic effect of metals and their compounds. During the formation of lacquers, a substantial proportion of the lighter fractions is volatilized. The remaining oil undergoes profound alterations owing to the formation, on the one hand, of gaseous and easily evaporated substances, and on the other, of products of oxidizing polymerization and condensation, which subsequently are transformed into lacquer films.

N. I. Chernozhukov and S. E. Craine have found that compounds of the lacquer type are condensation products of hydroxy acids. This was confirmed by Denis and Clyte in an experiment on an engine oil containing 0.1 to 0.3%

of hydroxy acids. The main bulk of most lacquer deposits consists of carbenes and carboids /26,32/.

Laboratory investigation has shown that lacquer formation in each oil will begin at a specific temperature which in turn will depend upon the test conditions. A rise in temperature will result in an increase in the amount of lacquer deposits. With a heavier fractional composition, the lacquer film forms more slowly but in larger amounts and the process begins at higher temperatures. Additives which counter the effect of hydroxy acids and improve the stability of oils will raise the temperature of the beginning of intensive lacquer formation. Very thin lacquer films on inoperative parts of the oil system may be considered as harmless, and in certain cases even useful for the protection of metal surfaces against corrosion. Dense lacquer deposits worsen the thermal conductivity of metal parts and may interfere with the normal operation of roller bearings.

L. I. Saranchuk used the Popok method (GOST 5737-53) /26/ to determine the tendency of gas turbine engine oils to form lacquer deposits. The oils were heated for 60 minutes at 250°. Lacquer was formed in the following amounts: MK-8 oil - 0.4%, transformer oil - 0.6%. Heavier aircraft engine oils, under the same conditions, after 30 minutes' heating, yielded the following amounts of lacquer: MK-22 - 6%, MS-20 - 20%. /32/. It will be seen that MK-8 and transformer oil produce less lacquer, according to this method. However, it must be borne in mind that the conditions of the method are substantially different from working conditions in jet engines. It is therefore not clear to what extent evaluation of lacquer forming properties of light oils according to this method reflects their behavior under operating conditions.

Hydrocarbon sediments are formed in gas turbine engines as a result of inadequate resistance to high temperature oxidation of the oils used. The sediments consist essentially of oxidizing polymerization products of the oil. Oils containing large amounts of aromatic hydrocarbons with condensed rings show a strong tendency to form insoluble oxidation products. Decomposition products insoluble in oil may be present in a finely dispersed state or as large particles. The first of these are less dangerous because they do not settle in the oil system. Decomposition products in the form of large particles produce sediments which clog up the oil ducts and pumps, settle in filters and bearings, as well as elsewhere in the oil system. The sediment may choke the injectors supplying oil to the working parts and impede the operation of machinery in which the oil is used as a working hydraulic liquid. All this may lead to serious malfunctioning of the engine /8, 26, 30, 31, 32/. The formation of sediments and resinous deposits on the working components of the bearings also occurred as a result of the separation of high polymer admixtures from the oil. Hunt /18/ states that viscous and resinous deposits would collect in the bearings during tests on oils containing polyisobutylene and polymethacrylate as a result of the evaporation of the oil, causing damage to the bearing housing.

Light oils of the MK-8 type form considerable amounts of sediment fairly quickly at high temperatures and in close contact with the air. V. V. Panov, studying the oxidation stability of MK-8 oil subjected to intense spraying and mixing with air, found that when the oil was oxidized for 5 hours, the sediment insoluble in isooctane, produced at 150°, was 0.1%, whereas at 175° it

was 0.5%.

Several types of lubricating petroleum oils are used in U.S. and British gas turbine engines /33/. The physical and chemical properties of some are given in Table 8.

Table 8

Physical and Chemical Properties of Gas Turbine Engine Oils  
Used in the U.S.A. and Britain

Indices	U.S. oil (according to AB)		British R.D. 2490 specifications oil
	1010	1005	
Specific gravity at 15.5°	0.864	-	0.880
Viscosity in centistokes at the following temperatures, in °C:			
98.9, not less than. . . . .	2.5	1.6	3.15
37.8, not less than. . . . .	10.0	5.0	13.0
-18 , not less than. . . . .	220	52	-
-40 , not more than. . . . .	3000	400	7000
-54 , not more than. . . . .	about 40000	not more than 3000	-
Viscosity index. . . . .	70	80	71
Solidification point, in °C. . . . .	-57	-59	-48
Flash point, in °C, not lower than .	129	107	154
Evaporation losses after 22 hours, at 98.9°C, % by weight . . . . .	about 8	about 20	-

Of particular note is the low viscosity of arctic oil 1005 at 98.9°, intended for use at very low temperatures. It differs from all the other known oils in having very low viscosity (400 centistokes at -40°), a feature which confers good starting properties on it and the ability to be readily pumped through the oil system at below-freezing temperatures. However, these favorable properties are offset by very high volatility. Losses due to evaporation when the oil is heated for 22 hours at 98.9° are as high as 20%, whereas in the case of 1010 oil they amount only to 8%. The viscosity of the British oil at 98.9° is only slightly higher than that of 1010 oil, but at -40° it increases very appreciably.

Tests conducted in the U.S.A. on oil 1010 in many types of turbojet engines have shown that this oil cannot fully meet the operating requirements of the more powerful engines operating at high temperatures. Insufficient oxidation resistance during high temperature operations, low wearing protection and pronounced volatility particularly at high altitudes led to various types of malfunctioning during flight. In high temperature areas, large amounts of the oil's decomposition products accumulated on the engine parts. Oil consumption due to evaporation was excessive. There was occasional evidence of scoring of gear teeth and wearing of frictional surfaces. In view of its inadequate

protection against wear, 1010 oil cannot be used in the majority of turbo-prop engines with high propeller reducer loads.

1100 oil, which is a highly viscous lubricating petroleum oil, and is used in aircraft piston engines, was tried out on turboprop engines. Some of the data for the oil are given in Table 9.

**Table 9**  
**Comparative Properties of U.S. Petroleum Oils**

Indices	Petroleum oil	
	1100	1010
Viscosity at 98.9°, in centistokes . . . .	20.5	2.5
Solidification point, °C . . . . .	Not higher than -12	-57
Flash point, °C . . . . .	250	145
Circulation limit, °C . . . . .	- 1	From -40 to -53
Oxidation stability and corrosiveness at 175°C . . . . .	Not stable, produces corrosion	
Load limit on gear teeth, kg/cm of tooth thickness (Ryder machine) . . . . .	576	32
Relative evaporation rate at 204°C, in % . . . . .	1	100
Oil consumption in engine . . . . .	Small	Very large

Engine tests have shown that 1100 oil ensures good lubrication of bearings and gear transmissions, including the propeller reducer. On the basis of a study of the wearing protection offered by the various oils on the Ryder machine (a description of the method is given in the last section of the book) and a comparison of the data on the behavior of oils in the engines, it was found /34, 35/ that oils which could withstand Ryder machine loads of the order of 304-400 kg per cm of tooth thickness, behaved quite satisfactorily in engines equipped with reducers. The data in Table 9 show that oil 1100, judged on the basis of the Ryder machine load limit, exceeds this value by a considerable amount. The relationship established experimentally between the Ryder machine load limit and lubricating oil viscosity is given in Figure 13.

The oil consumption was small, but there was carbon deposit formation on parts of some of the engines. This shows that the oxidation resistance of 1100 oil was not entirely satisfactory. Moreover, the high viscosity of 1100 oil at low temperatures and its high solidification point caused difficulties during low temperature starting of the engine and operation of regulating mechanisms. The oil could be pumped through the engine only at temperatures down to -1°.

For the purpose of comparing the properties of light and heavy petroleum oils, Table 9 also lists the basic operational characteristics of 1100 oil. An examination of these data shows that 1100 oil is greatly superior to 1010



oil in regard to load limit, volatility and oil consumption in the engine. 1100 oil evaporates 100 times more slowly than 1010 oil. The only advantage of 1010 oil is its good viscosity at low temperatures which permits it to circulate through the engine oil system at temperatures of  $-40^{\circ}$  and  $-53^{\circ}$ . The oils were deemed to be similar in regard to oxidation resistance and corrosiveness.

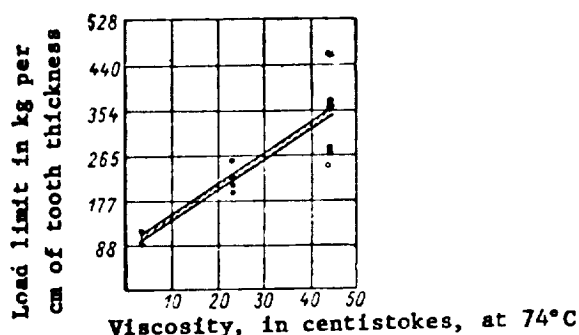


Fig. 13. Relationship between viscosity and permissible load on Ryder machine.

A comparison of the physical and chemical characteristics and engine behavior of light and heavy lubricating petroleum oils for gas turbine engines shows that it is difficult to combine in one type of oil all of the properties required in the proper operation of modern turbojet and turboprop engines.

Improvements in the properties of petroleum oils for gas turbine engines depend upon further developments in production processes which make it possible to obtain oils with operationally more desirable fractional and chemical compositions. Great possibilities in the improvement of oil properties are offered by the use of special additions and admixtures which impart operationally essential properties to the oils. Additives to engine and industrial oils have found wide application in recent years. All the basic properties of oils (viscosity, high temperature, oxidation resistance, wearing protection, etc.) may be substantially improved by the additives. Some additives are known for their ability to reduce oil corrosiveness, to lower frothing and to impart other desirable properties [8, 25, 26, 30, 36, 37]. According to Hunt [18], in Britain, in order to improve the lubricating properties of certain petroleum oils, additions of 1% sulfur and phosphorus and 1% stearic acid were made.

In the selection of oil additives it is necessary to take into account the effectiveness of the additives themselves and the ability of the oils to absorb them. The latter depends on the hydrocarbon composition of the oils and the type of refinement. A. M. Kuliev, R. S. Kuliev and M. I. Aliev [38], have shown that depressant and anti-oxidizing additives are well absorbed by

paraffin and naphthene hydrocarbons, but that their effect is paralysed by aromatic and resinous hydrocarbons.

The difficulties encountered in obtaining lubricating petroleum oils for aircraft gas turbine engines, which would be oxidation resistant at high temperatures and which would meet all of the other requirements, have led to the search for synthetic oils based on aliphatic esters as well as organic silicates and other compounds.

## Chapter IV

### SYNTHETIC LUBRICATING OILS

In recent years very great attention has been devoted to seeking out and analysing the properties of essentially new aircraft gas turbine engine lubricating oils. In terms of oxidation resistance at different temperatures and other properties, these oils are required to be substantially superior to petroleum oils. All known synthetic lubricating oils consist of hydrocarbons or of different types of organic compounds containing oxygen. Among the latter, those which have attracted the greatest attention of researchers are aliphatic esters, polyalkylene glycols, silicon-organic compounds and certain other products. Some of these compounds have already been applied on a large scale, as lubricants in engines and various other mechanisms.

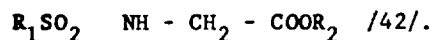
Production of synthetic hydrocarbon oils is primarily based on polymerization of unsaturated hydrocarbons and alkylation of aromatic hydrocarbons /8, 30, 39, 40/. As initial raw materials for polymer oils various unsaturated hydrocarbons, cracking process distillates and other products having a high unsaturated hydrocarbon content may be used. Polymerization of unsaturated hydrocarbons is carried out in the presence of aluminum chloride, boron fluoride, phosphoric or sulfuric acid and other catalysts.

Oils obtained from the cracking of different types of Grozny paraffin-base petroleum had a low specific gravity, a low solidification point and a very flat viscosity-temperature curve. They had good oxidation resistance. Passage of air through the oil for 24 hours at 150° did not produce any sediments /25/.

M. G. Rudenko and V. N. Gromova claim to have derived from the unsaturated hydrocarbon 2-methyloctadecene-2, an oil with a viscosity index of 128, indicating a very flat temperature-viscosity curve /41/.

In Germany, during the war, VS-1 and SS-163 oils were used in jet engines and LTK-12 oil in torpedoes. These were mixtures of the high-polymer product SS-903 and aliphatic esters.

Table 10 lists the composition and some of the properties of these oils. Product SS-903 was obtained by polymerization of ethylene at 240°. It consisted exclusively of isoparaffin hydrocarbons and had a viscosity of about 20 centistokes at 100°, about 108 centistokes at 50°, and a solidification point below -30°. As will be seen from Table 10, the basic components of the oil were those of product E-515, i.e. a mixture of adipic and methyladipic acid esters and technical synthetic isobutyl alcohol. The anticorrosion admixture KSE added to the oil was an ester with the following composition



In Germany, in order to increase the oxidation stability of synthetic polymer oils, aromatic esters were added during polymerization of olefins, or aromatic hydrocarbons were alkylated with polymerized hydrocarbons.

Table 10

Composition and Properties of Synthetic Oils for Jet Engines and Torpedoes

Indices	VS-1 or SS-1631 oil	LTK-12 oil
Percentage content of		
polymer product SS-903 . . . . .	25	35
isobutyl adipate and methyladipate (product E-515) . . . . .	72	63
KSE additive . . . . .	3	2
Viscosity in centistokes, at temperatures in °C of:		
98.9 . . . . .	10.7	-
50.0 . . . . .	-	87-95
37.8 . . . . .	21.3	-
Viscosity index . . . . .	149	-
Solidification point in °C . . . . .	below -45	below -59

Tests of certain polymer oils on automobile, diesel and aircraft piston engines have shown that they have better stability than ordinary petroleum lubricating oils.

The basic primary components in the production of lubricating oils by alkylation are the aromatic hydrocarbons (benzene, xylene, naphthalene, etc.) and the unsaturated hydrocarbons or halogen paraffin series hydrocarbons and alcohols. Aluminum chloride has been used as a catalyst.

The synthetic oils obtained in Germany through the condensation of chlorinated paraffins with naphthalene had good oxidation resistance, but were inferior to polymer and other oils as regards the viscosity-temperature relationship.

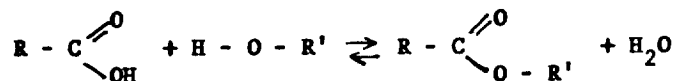
As compared to natural petroleum oils, synthetic oils have a more definite and limited composition, which is an advantage. Current knowledge of hydrocarbon transformation makes it possible to direct synthetic processes in such a way as to obtain lubricating oils with a chemical composition which better meets stringent requirements. The development of hydrocarbon oil production has been limited owing to the high cost involved.

### Lubricating Oils Based on Aliphatic Esters

Of all the synthetic liquids considered as prospective lubricating oils, the most thoroughly studied were the carboxylic acid esters. In Germany alone, from 1938 to 1944, more than 3500 esters of different molecular weight and structure were produced and studied /42, 43/. The basic purpose of the large scale research operation was to find oils having a high oxidation resistance, combined with good viscosity, a low solidification point, the requisite lubricating properties and low volatility.

In Germany, some of the esters mixed with synthetic hydrocarbon oils were used as lubricating oils for aircraft and automobile engines and instruments, and as liquids for hydraulic mechanisms. Research was conducted during the same period in the United States. It was found that the most promising lubricating oils for precision instruments, weapons and aircraft gas turbines were the esters of dibasic acids. In the United States, it is stated /39/, certain oils were obtained from 2-ethylhexyl alcohol sebacate and were then mixed with viscous petroleum fractions.

Aliphatic esters may be considered as organic acids in which the carboxyl hydrogen is replaced by a hydrocarbon radical. Their general formula is  $R-C(=O)-O-R'$ . Esters are normally obtained by esterification, which is the direct interaction of an alcohol and an acid.



The esterification process is reversible. The reaction between an ester and water leading to the formation of an acid and an alcohol, is called saponification.

The alcohols entering into esters contain a hydroxyl group -OH linked with the hydrocarbon radical R-OH. Replacement of an hydroxyl for two, three or more hydrogen atoms in hydrocarbons produces diatomic, triatomic and in general polyatomic alcohols. Normally, diatomic alcohols are called glycols. Triatomic alcohols were given the name of glycerines. The simplest quadriatomic alcohol is erythrite.

Simple ethers, in which oxygen is linked to two identical or different hydrocarbon radicals R-O-R' are likewise encountered in the chemistry of synthetic oils.

Table 11 shows the structure and lists some of the properties of most of the alcohols which go to make up esters studied or used as lubricating oils.

The melting point of alcohols depends upon their structure, the existence of side chains and the arrangement of the hydroxyl group. For instance, isoamyl alcohol, which has a side methyl group at the third carbon atom, solidifies at a much lower temperature than normal amyl alcohol. The transfer of the hydroxyl group of octyl alcohol to the second carbon atom likewise lowers the solidification point. Of great interest, due to their structure, are the tri-methylolethane and pentaerythrite. In all of these

polyatomic alcohols, all the hydroxyl groups are located at the primary carbon atom linked with only one other carbon atom. This will be shown to be of great importance to the stability of the resulting products.

**Table 11**  
**Structure and Physical Properties of Alcohols**

Alcohol name and structure	Melting point, °C	Boiling point, °C	Specific gravity, $d_4^{20}$
n-Amyl (pentanol-1) $\text{CH}_3-(\text{CH}_2)_3-\text{CH}_2-\text{OH}$	-78.2	137.8	0.8144
Isoamyl (3-methylbutanol-1) $\text{CH}_3-\underset{\text{CH}_3}{\text{CH}}-\text{CH}_2-\text{CH}_2-\text{OH}$	-117.2	131.6	0.8110
n-Octyl $\text{CH}_3-(\text{CH}_2)_6-\text{CH}_2-\text{OH}$	-16.3	195.0	0.8246
n-Octyl (secondary) $\text{CH}_3-(\text{CH}_2)_5-\underset{\text{OH}}{\text{CH}}-\text{CH}_3$	-38.6	178.5	0.8193
Isooctyl (2-ethylhexanol-1 or 2-ethylhexyl) $\text{CH}_2-(\text{CH}_2)_3-\underset{\text{C}_2\text{H}_5}{\text{CH}}-\text{CH}_2-\text{OH}$	below -76.0	183.5	0.8328
n-Dodecyl (dodecanol) $\text{CH}_3-(\text{CH}_2)_{10}-\text{CH}_2-\text{OH}$	+24.0	257	0.831 (at melting point)
Ethylene glycol (ethanediol) $\text{CH}_2\text{OH}-\text{CH}_2-\text{OH}$	-13.2	197.2	1.114
Hexylene glycol (hexanediol 1 : 6) $\text{OH}-\text{CH}_2-(\text{CH}_2)_4-\text{CH}_2-\text{OH}$	42.0	250	-
Diethylene glycol $\text{OH}-\text{CH}_2-\text{CH}_2-\text{O}-\text{CH}_2-\text{CH}_2-\text{OH}$	-10.4	245	1.1177
Triethylene glycol $\text{OH}-\text{CH}_2-\text{CH}_2-\text{O}-\text{CH}_2-\text{CH}_2-\text{O}-\text{CH}_2-\text{CH}_2-\text{OH}$	-7.2	287.4	1.1254
Glycerine $\text{CH}_2-\text{OH}-\text{CH}-\text{OH}-\text{CH}_2-\text{OH}$	17	290 (for limited decomposition)	1.260
Trimethylolethane $\text{CH}_3-\underset{\text{CH}_2-\text{OH}}{\overset{\text{CH}_2-\text{OH}}{\text{C}}}-\text{CH}_2-\text{OH}$	199	-	-
Erythrite (tetrahydroxybutane-1:2:3:4) $\text{OH}-\text{CH}_2-\text{CH}-\text{OH}-\text{CH}-\text{OH}-\text{CH}_2-\text{OH}$	121.5	329.3	-
Pentaerythrite $\text{OH}-\text{CH}_2-\underset{\text{OH}-\text{CH}_2}{\overset{\text{CH}_2-\text{OH}}{\text{C}}}-\text{CH}_2-\text{OH}$	260	-	-

Carboxylic acids entering into esters used as lubricating oils are organic acids containing a monovalent carboxyl group  $\text{-}\overset{\text{O}}{\underset{\text{OH}}{\text{C}}}$  linked to a hydrocarbon radical. Depending upon the number of carboxyls per molecule, carboxylic acids are monobasic or polybasic, having two or more carboxyl groups.

Table 12 lists the essential characteristics of high molecular weight carboxylic acids. Dibasic (adipic, methyladipic, sebacic) and certain monobasic acids form part of many of the esters examined as prospective lubricating oils, hydraulic liquids, consistent grease components and other products. Some of the esters have found application as lubricants in engines and various types of machines and mechanisms. As may be seen, apart from enanthic acid, all of the others have a melting point above  $0^\circ$ . The side group introduced into adipic acid lowers the melting point considerably.

**Table 12**

**Structure and Physical Properties of Carboxylic and Dicarboxylic Acids**

Acid name and structure	Melting point, $^\circ\text{C}$	Boiling point, $^\circ\text{C}$	Specific gravity, $d_4^{20}$
Enanthic (heptanoic) $\text{CH}_3\text{-(CH}_2)_5\text{-COOH}$	-10.5	223	0.9184
Caprylic (octanoic) $\text{CH}_3\text{-(CH}_2)_6\text{-COOH}$	-16.2	237	0.9100
Pelargonic (nonanoic) $\text{CH}_3\text{-(CH}_2)_7\text{-COOH}$	12.5	253	0.9057
Glutaric (pentanoic) $\text{HOOC-(CH}_2)_3\text{-COOH}$	97.5	-	-
Adipic $\text{HOOC-(CH}_2)_4\text{-COOH}$	153.5	265 at 100 mm	1.3660
Methyladipic $\text{HOOC-CH}_2\text{(CH}_2)_2\text{-CH(CO}_2\text{CH}_3\text{)-COOH}$	64.0	216-220 at 28 mm	-
Azelaic $\text{HOOC-(CH}_2)_7\text{-COOH}$	106.6	287 at 100 mm	-
Sebacic $\text{HOOC-CH}_2\text{-(CH}_2)_6\text{-CH}_2\text{-COOH}$	134.5	295	-

**Properties of Aliphatic Esters**

According to many researchers, monoethers containing only monatomic alcohols and monobasic acids do not offer encouraging prospects as oxidation-resistant lubricating oils with a low solidification point. Their solidification point is relatively high and the viscosity-temperature curve is rather steep. Among this category of compounds, there are few liquids with properties capable of meeting the requirements expected of synthetic lubricating oils for gas turbine engines. It is considered that only the properties of monopelargonates  $\text{CH}_3\text{-(CH}_2)_7\text{-COOH}$  might be of interest as possible bases for

synthetic turboprop lubricating oils. Not all the monoethers have adequate lubricating properties. Some of them are highly volatile. Of considerable interest are the aliphatic esters of polyatomic alcohols and polybasic acids. Many of them have already been widely applied as lubricating oils for engines and instruments, and also as greases, hydraulic and other technical liquids. The structure and properties of some of them are shown in Tables 13 and 14.

A comparison of the chemical structures of esters and their viscosity characteristics and solidification points shows that introducing side methyl and ethyl groups substantially lowers the solidification point, but that at the same time, index  $m$ , which determines the gradient of the viscosity-temperature curve according to the ASTM diagram, increases somewhat, indicating a deterioration of the viscosity-temperature characteristic of the product. Thus, normal dioctyl adipate has a solidification point of  $4^{\circ}$  and a gradient index  $m$  of the curve of 2.75. The introduction into this ester of only one methyl group lowered the solidification point down to  $-32^{\circ}$  and raised the index  $m$  to 3.46. With a side ethyl group in the ethylhexylate, the solidification point of the product was lowered by  $82^{\circ}$  as compared to normal octyl ester. A similar effect by side groups was noted in the case of polyatomic alcohol esters.

The second and sixth 2-ethylhexanates listed in Table 14, with a side ethyl group, solidify at a much lower temperature than the first and fifth normal octanates (caprylates) which contain the same number of carbon atoms as 2-ethylhexanoic acid. A low solidification point is also possessed by diethylene glycol and triethyleneglycol esters.

An increase in carbon atoms in the principal chain results in an increase in viscosity. Thus, the third and sixth ethylhexyl alcohol esters (Table 13) are remarkable for the fact that the sixth ester obtained from a higher molecular weight sebacic acid has a viscosity which is nearly twice as large (23.2 centistokes) as that of the third (12.8 centistokes). The fifth ester which contains the high molecular weight dodecyl alcohol  $C_{12}H_{25}OH$ , has high viscosity and a high solidification point. A more pronounced effect upon increased ester viscosity is produced by the introduction of the benzene ring into the molecule.

It will be seen from Table 13 that di-2-ethylhexyl phthalate containing 24 atoms of carbon per molecule has a viscosity at  $20^{\circ}$  of 121.0 centistokes, which is five times greater than that of di-2-ethylhexyl sebacate though the latter contains 26 carbon atoms per molecule.

Further data on the viscosity and solidification point of the most thoroughly studied diesters are given in Table 15. These compounds likewise illustrate the strong influence of the structure of side groups and their arrangement within the ester molecule upon viscosity and solidification point.

The lubricating properties, oxidation stability, volatility and other physical and chemical characteristics of ester oils are likewise determined by their structure. Owing to the presence in the molecule of active polar groups, esters adsorb and orient well on metallic surfaces, forming resistant films which provide excellent protection against wear, to the



**Table 13**  
**Esters of Dibasic Carboxylic Acids**

Ester name and structure	Speci- fic gravi- ty	Viscosity in centistokes at tempera- tures of:		Gradient of viscosity- temperature curve ac- cording to ASTM, index, m	Solli- difi- cation point, °C	Flash point °C
	$d_4^{20}$	20°	99°			
<b>Di-octyl adipate</b> $\begin{array}{c} \text{CH}_2-\text{CH}_2-\text{COO}-\text{C}_8\text{H}_{17} \\   \\ \text{CH}_2-\text{CH}_2-\text{COO}-\text{C}_8\text{H}_{17} \end{array}$	0.919	14.8	2.85	2.75	4	215
<b>Di-octyl 1-methyladipate</b> $\begin{array}{c} \text{CH}_3 \\   \\ \text{CH}_2-\text{CH}-\text{COO}-\text{C}_8\text{H}_{17} \\   \\ \text{CH}_2-\text{CH}_2-\text{COO}-\text{C}_8\text{H}_{17} \end{array}$	0.927	16.8	2.66	3.46	-32	208
<b>Di-2-ethylhexyl adipate</b> $\begin{array}{c} \text{C}_2\text{H}_5 \\   \\ \text{CH}_2-\text{CH}_2-\text{COO}-\text{CH}_2-\text{CH}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{CH}_2-\text{CH}_2-\text{COO}-\text{CH}_2-\text{CH}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{C}_2\text{H}_5 \end{array}$	0.925	12.8	2.26	3.55	-78	215
<b>Di-2-ethylhexyl methyladipate</b> $\begin{array}{c} \text{CH}_3 \quad \text{C}_2\text{H}_5 \\   \quad   \\ \text{CH}_2-\text{CH}-\text{COO}-\text{CH}_2-\text{CH}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{CH}_2-\text{CH}_2-\text{COO}-\text{CH}_2-\text{CH}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{C}_2\text{H}_5 \end{array}$	0.910	18.0	2.61	3.65	-72	212
<b>Didodecyl 1-methyladipate</b> $\begin{array}{c} \text{CH}_3 \\   \\ \text{CH}_2-\text{CH}-\text{COO}-\text{CH}_2-(\text{CH}_2)_{10}-\text{CH}_3 \\   \\ \text{CH}_2-\text{CH}_2-\text{COO}-\text{CH}_2-(\text{CH}_2)_{10}-\text{CH}_3 \end{array}$	0.913	36.13	4.28	3.23	-16	231
<b>Di-2-ethylhexyl sebacate</b> $\begin{array}{c} \text{C}_2\text{H}_5 \\   \\ \text{CH}_2-(\text{CH}_2)_3-\text{COO}-\text{CH}_2-\text{CH}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{CH}_2-(\text{CH}_2)_3-\text{COO}-\text{CH}_2-\text{CH}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{C}_2\text{H}_5 \end{array}$	0.912	23.2	3.30	3.40	-72	235
<b>Di-2-ethylhexyl phthalate</b> $\begin{array}{c} \text{C}_2\text{H}_5 \\   \\ \text{C}_6\text{H}_4 \begin{array}{l} \text{COO}-\text{CH}_2-\text{CH}-(\text{CH}_2)_3-\text{CH}_3 \\ \text{COO}-\text{CH}_2-\text{CH}-(\text{CH}_2)_3-\text{CH}_3 \end{array} \\   \\ \text{C}_2\text{H}_5 \end{array}$	0.990	121.0	5.04	4.19	-42	178

**Table 14**  
**Esters of Polyatomic Alcohols**

Ester name and structure	Specific gravity	Viscosity in centistokes at temperatures of:		Gradient of viscosity-temperature curve according to ASTM, index, $\frac{m}{m}$	Solidification point, °C
	$d_4^{20}$	20°	99°		
1.6 hexyleneglycol caprylate $\begin{array}{c} \text{CH}_2-\text{CH}_2-\text{CH}_2-\text{OOC}-(\text{CH}_2)_6-\text{CH}_3 \\   \\ \text{CH}_2-\text{CH}_2-\text{CH}_2-\text{OOC}-(\text{CH}_2)_6-\text{CH}_3 \end{array}$	0.920	14.4	2.62	3.33	8
1.6 hexyleneglycol 2-ethylene hexanate $\begin{array}{c} \text{CH}_2-\text{CH}_2-\text{CH}_2-\text{OOC}-\overset{\text{C}_2\text{H}_5}{\text{CH}}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{CH}_2-\text{CH}_2-\text{CH}_2-\text{OOC}-\underset{\text{C}_2\text{H}_5}{\text{CH}}-(\text{CH}_2)_3-\text{CH}_3 \end{array}$	0.923	16.6	2.21	4.0	-78
Diethyleneglycol pelargonate $\begin{array}{c} \text{CH}_2-\text{CH}_2-\text{OOC}-(\text{CH}_2)_7-\text{CH}_3 \\   \\ \text{CH}_2-\text{CH}_2-\text{OOC}-(\text{CH}_2)_7-\text{CH}_3 \end{array}$	0.9428	14.7	-	-	-51
Triethyleneglycol pelargonate $\begin{array}{c} \text{CH}_2-\text{O}-(\text{CH}_2)_2-\text{OOC}-(\text{CH}_2)_7-\text{CH}_3 \\   \\ \text{CH}_2-\text{O}-(\text{CH}_2)_2-\text{OOC}-(\text{CH}_2)_7-\text{CH}_3 \end{array}$	0.9576	18.1	-	-	-60
Trimethylolthane caprylate $\begin{array}{c} \text{CH}_2-\text{OOC}-(\text{CH}_2)_6-\text{CH}_3 \\   \\ \text{CH}_3-\text{C}-\text{CH}_2-\text{OOC}-(\text{CH}_2)_6-\text{CH}_3 \\   \\ \text{CH}_2-\text{OOC}-(\text{CH}_2)_6-\text{CH}_3 \end{array}$	0.944	36.2	3.86	3.57	- 8
Trimethylolthane 2-ethylhexanate $\begin{array}{c} \text{CH}_2-\text{OOC}-\overset{\text{C}_2\text{H}_5}{\text{CH}}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{CH}_3-\text{C}-\text{CH}_2-\text{OOC}-\overset{\text{C}_2\text{H}_5}{\text{CH}}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{CH}_2-\text{OOC}-\underset{\text{C}_2\text{H}_5}{\text{CH}}-(\text{CH}_2)_3-\text{CH}_3 \end{array}$	0.948	49.3	3.14	3.88	-63
Pentaerythrite 2-ethylhexanate $\begin{array}{c} \text{CH}_2-\text{OOC}-\overset{\text{C}_2\text{H}_5}{\text{C}}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{C}-\text{CH}_2-\text{OOC}-\overset{\text{C}_2\text{H}_5}{\text{C}}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{CH}_2-\text{OOC}-\overset{\text{C}_2\text{H}_5}{\text{C}}-(\text{CH}_2)_3-\text{CH}_3 \\   \\ \text{C}-\text{CH}_2-\text{OOC}-\underset{\text{C}_2\text{H}_5}{\text{C}}-(\text{CH}_2)_3-\text{CH}_3 \end{array}$	0.962	132.5	6.32	3.82	-10

frictional components. The addition of esters to mineral oils may substantially lower the coefficient of friction and frictional surface wear. For instance, the addition of 5% of butyl phthalate to a mineral oil increases the allowable load in the determination of wearing properties on the Timken machine /44/ by approximately 83%.

Table 15

Properties of Diesters at low temperatures

Diester name	Molecular weight	Viscosity, centistokes, at temperatures of:		Freezing point, °C
		98.9°	-40°	
Di-2-ethylhexylglutarate . . . .	356.5	2.17	715	-62
Di-3-methylbutyladipinate . . . .	288.4	1.73	171	-42
Di-2-ethylhexyladipinate . . . .	370.6	2.38	807	-67
Di-1-ethylpropylazelainate . . . .	328.5	2.10	429	-77
Di-3-methylbutylazelainate . . . .	328.5	2.20	286	-47
Di-2-ethylhexylazelainate . . . .	412.5	3.06	1190	-77
Di-1-ethylpropylsebacate . . . .	242.5	2.28	504	-18
Di-2-ethylhexylsebacate . . . .	426.7	3.32	1410	-55
Triethyleneglycol-di-2-ethylhexanate . . . . .	402.5	2.41	1890	-52
1.6-hexamethyleneglycol-di-2-ethylhexanate . . . . .	370.6	2.35	1090	-62
1.10-decamethyleneglycol-di-2-ethylhexanate . . . . .	426.6	3.26	1850	-62

It is known that castor oil, which consists essentially of glycerine esters derived from unsaturated ricinoleic hydroxy acid  $C_{17}H_{32}(OH) \cdot COOH$ , has good lubricating properties (oiliness). It was formerly widely used as a lubricating oil in certain types of aircraft piston engines and provided better wear resistance for frictional components than petroleum oils /45/. In the study of synthetic products with a view to using them as lubricating oils, considerable attention is given to their volatility. Aliphatic esters derived from carboxylic acids are less volatile than the related hydrocarbon-based oils and many synthetic liquids of different composition. Table 16 gives comparative data on the vapor tension of some synthetic products of various compositions at 180°.

According to Table 16, the lowest vapor tension is that of sebacic acid ester, in spite of the fact that this compound has very low viscosity as compared to others with a higher vapor tension.

The second in line as regards vapor tension is the hydrocarbon 7.12-dimethyl-9.10-dihexyloctadecane, which has a vapor tension of  $5.1 \times 10^{-4}$  atm for a relatively high viscosity value of 14.4 centistokes. The highest vapor tension is possessed by fluorinated compounds and certain silicon organic compounds.

**Table 16****Vapor Tension of Synthetic Liquids**

Compound	Viscosity at 50°, centistokes	Vapor tension at 180° at. x 10 <sup>-4</sup>
7.12-dimethyl-9, 10-dihexyloctadecane (hydrocarbon)	14.4	5.1
1.6-diphenylhexane (hydrocarbon) . . . . .	4.2	78
Di-2-ethylhexyl sebacate . . . . .	8.8	2.3
Cyclic polymer siloxane liquids:		
DS 701 . . . . .	5.0	170
DS 702 . . . . .	12	20
Cyclic polysiloxane liquid . . . . .	4.1	2000
3.3-diphenyltrisiloxane . . . . .	3.9	4000
Fluorinated lubricating oil . . . . .	15	600
Carbon tetrafluoride oil . . . . .	3.8	3000

The volatility of diesters of carboxylic acids, determined through the weight loss after heating for 168 hours at 65.6° in a thermostat, is given in Table 17.

**Table 17****Volatility of Diesters**

Diester	Evaporation loss, weight %	Molecular weight	Viscosity at 98.9° centistokes
Di-2-ethylhexyl glutarate . . . . .	4.40	356.5	2.17
Di-2-ethylbutyl adipate . . . . .	0.34	314.5	-
Di-2-ethylhexyl adipate . . . . .	0.07	370.6	2.26
Di-2-ethylbutyl azelate . . . . .	0.05	356.5	-
Di-2-ethylhexyl azelate . . . . .	0.05	412.5	3.06
Di-2-ethylhexyl sebacate . . . . .	0.05	426.7	3.30

The highest volatility was that of di-2-ethylhexyl glutarate.

Oxidation stability at high temperatures is the most important characteristic of gas turbine engine oils. Not all carboxylic acid esters have sufficient stability at high temperatures. The use of castor oil in aircraft piston engines has shown that it is not sufficiently stable at high temperatures. Its decomposition leads to the formation of acids which corrode engine parts and of gluey, lacquery, resinous substances which cause burning up of piston rings and produce other engine defects. If kept for a long time, castor oil will likewise gradually decompose and will liberate metal-corroding acids.

Tests have shown /42, 43/ that the cause of instability of castor and other vegetable oils containing glycerine esters is the poor stability of glycerine. Glycerine has a secondary hydroxyl group connected to the middle carbon atom linked to other carbon atoms. The secondary hydroxyl group is not very stable thermally and this is the reason for the decomposition of glycerine esters. Upon heating, the secondary hydroxyl tends to hydrolyze, forming free acid. A double carbon link is formed in the ester, leading to a further oxidation and polymerization of the molecule. A study of the stability of oils by oxidation with oxygen has shown that, at 125° in the course of one day, castor oil consumes 14 mg of oxygen per gram of oil in oxidation, whereas mineral oil under the same conditions, consumes only 0.7 to 1.5 mg of oxygen /44/.

These conclusions have been borne out by a study of the properties of synthetic esters of high molecular weight acids and triatomic trimethylol-ethane alcohol containing primary hydroxyl groups located at carbon atoms linked to only one carbon atom. Engine tests of this ester have shown that along with good lubricating properties, it also has substantial resistance to oxidation at high temperatures.

Esters containing other polyatomic alcohols without secondary hydroxyls (ethylene glycol, erythrite, pentaerythrite), whose structure was given in Table 11, are likewise highly stable. Nevertheless, the oxidation stability of aliphatic esters is still lower than that required for gas turbine engines. To improve this property, antioxidant admixtures are introduced into the esters.

Investigations conducted by Cohen, Murphy et al /46/ have shown that it is possible to select sufficiently effective additives, which will give good oxidation protection to the esters at temperatures of 150° and higher.

The stabilizing effect of antioxidants was studied on di-2-ethylhexyl sebacate. Oxidation was induced by means of air in the presence of metal catalysts (steel, copper, duralumin). The stability criteria were induction time (time by which oxidation products begin to form), alteration in viscosity, color and acid number and the formation of resinous and lacquery sediments. In addition, variations in the weight of metal plates placed in the oil were determined and their external appearance was noted. An investigation was made of the antioxidant effectiveness of a great many different products including derivatives of phenothiazine, amine and phenol compounds, phosphorus-containing substances, metals, organic products and many others. Table 18 shows the results of the oxidation of di-2-ethylhexyl sebacate, pure and containing phenothiazine, which is the most effective antioxidant as well as one of the derivatives of this compound /47, 49, 50, 51, 52, 53, 54/.

#### Application of Ester Lubricating Oils

Research into the structure and properties of a large number of organic compounds of different composition has made it possible to derive various types of synthetic lubricating oils for aircraft gas turbine engines. After a preliminary examination of the physical and chemical properties of synthetic oils of various compositions, some of them were recommended in the USA in

1947 for testing on turbojet engines /38/. The essential physical and chemical properties of the oils are listed in Table 19. All oils recommended for testing contained additives improving high temperature oxidation resistance.

Table 18

Stability of Di-2-ethylhexyl Sebacate

Product	Anti-oxidant conc. wt. %	Temperature °C	Induction time, hrs.	Viscosity increase at 37.8° as % of initial value	Acid number, mg KOH	
					Volatile acids	Non-volatile acids
Di-2-ethylhexyl sebacate	0.0	100	72	14	5.5	5.3
Same	0.0	150	12	1000	83	22
Same, with the following antioxidant:						
Phenothiazine	0.47	163	>168	< 1.0	0.28	1.0
"	0.94	175	>168	3.8	3.3	2.2
3,7-difluorophenothiazine	1.0	175	168	2.7	1.0	2.2

Ester oils have substantially better viscosity than petroleum oil 1010. This may be seen from the viscosity ratio  $v_{-54}/v_{37.8}$ . The viscosity ratio of all synthetic oils is approximately one-fifth that of petroleum oil. Synthetic oils are also better than mineral oil with respect to all the other constants, particularly volatility. The most favorable indices were displayed by di-2-ethylhexyl sebacate.

The first diester tests conducted in 1947 gave favorable results. Further laboratory work was carried out afterwards to study the properties of aliphatic esters. Special tests of diesters on reducing gear installations at various loads have shown that additives had to be used to improve their anti-wear properties. The first anti-wear additive was tricresyl phosphate. However, its addition substantially raised oil viscosity at -54°.

In view of the increased oxidation ability required of gas turbine engine lubricating oils with variations in temperature, further studies were made of oil oxidation stability at high temperatures, under various conditions. In the United States, in addition to a study of stability and corrosiveness on various metals at 175°, an evaluation was made of the oil's coking properties when sprayed on a metal surface at 315.6°. High temperature tests of oils in roller bearings at temperatures from 280° to 371° have also been conducted.

A comparative study of the oxidation stability of ester and petroleum oils conducted by different methods has shown that ester oils containing effective antioxidants are considerably better than petroleum oils. The coking properties of various oils sprayed on a metal surface at 315.6° for 8 hours

are given below:

	<u>Amount of coke in mg</u>
Organic phosphorus oils	about 500
Organic silicic acid esters	" 400
Petroleum oil	" 250
Diesters	" 20

Table 19

**Physical and Chemical Properties of Ester and Petroleum Oils  
for Gas Turbine Engines**

<b>Indices</b>	<b>Diisooctyl adipate</b>	<b>Di-2- ethylhexyl azelate</b>	<b>Di-2- ethylhexyl sebacate</b>	<b>Petroleum oil 1010 according to MIL-O- 6081 spe- cifica- tions</b>	<b>Synthetic oil re- quirements according to MIL-L- 7808 spe- cifica- tions</b>
<b>Viscosity, in centi- stokes, at temp- eratures of:</b>					
98.9 . . . . .	2.8	3.1	3.3	2.5	not less than 3.0
37.8 . . . . .	10.0	11.4	12.6	10.3	" " 11.0
-18 . . . . .	135	156	187	220	--
-40 . . . . .	1040	1190	1410	2600	--
-54 . . . . .	7000	8000	8600	40000	not more than 13000
Viscosity index . . . .	141	146	154	70	--
<b>Viscosity ratio:</b>					
$\frac{v_{-54}}{v_{37.8}}$ . . . . .	70	70	68	388	-
<b>Temperatures, °C, for</b>	<b>below</b>	<b>below</b>	<b>below</b>	<b>below</b>	<b>not higher</b>
loss of fluidity . . .	-59	-59	-55	-59	than -59
flash point . . . . .	188	229	232	149	not lower than 196
ignition point. . . .	221	243	254	-	-
<b>Evaporation loss, after</b>					
22 hours at 98.9°, wt.%	1	0.2	0.1	Approx 8.0	-
<b>Stability at 175° . . .</b>	<b>Stable</b>	<b>Stable</b>	<b>Stable</b>	<b>Not stable</b>	<b>-</b>
<b>Corrosion at 175° . . .</b>	<b>Not Corrosive</b>	<b>Not Corrosive</b>	<b>Not Corrosive</b>	<b>Corrodes</b>	<b>-</b>

These data show that diesters give considerably better results than petroleum or other organic phosphate or silicate synthetic oils.

Synthetic oils were widely bench- and flight-tested in the United States and Britain on all the existing types of gas turbine engines /35/. Three brands of synthetic oils, A, B and C, were selected which had different viscosities and were prepared from different aliphatic esters with additives to improve their lubricating properties and oxidation resistance.

Tables 20 to 22 show that, judged by their load bearing capacity, synthetic oils were substantially better than basic turbojet engine petroleum oil 1010. The best anti-wear properties were those of the most viscous oil A. On the basis of this index, it was superior to the high grade petroleum oil 1100. All three ester oils had high flash points and in this respect they differed sharply from petroleum oils having the same viscosity. All diester oils showed good results in regard to oxidation stability at 175°.

With respect to viscosity at low temperatures, on which engine starting depends, oils B and C were close to one another and considerably better than oil A. The viscosities of 5000 and 20000 centistokes given in Table 21 are limiting values permitting circulation through the oil system. At a viscosity of 5000 centistokes normal oil circulation is disrupted. When the viscosity reaches 20 000, supply of oil to frictional assemblies ceases.

Although petroleum oil 1010 has a lower viscosity at 98.9° than oils B and C, it is markedly inferior to them as regards circulation at low temperatures. Table 22 gives volatility results for ester and petroleum oils as a percentage of the volatility of 1010 oil.

**Table 20**  
**Properties of Engine-Tested Synthetic and Petroleum Oils**

Indices	<u>Synthetic ester oil</u>			<u>Mineral oil</u>	
	A	B	C	1010	1100
				for jet engines	for piston engines
Viscosity at 98.9°C, centistokes	7.9	3.6	3.1	2.5	20.5
Maximum permissible load on bearing transmissions, as % of load when 1100 oil is used	105	50	45	15	100
Flash point, °C	232	221	204	146	252
Oxidation resistance and corrosiveness at 175°C	Stable, will not attack metals			Unstable, will attack metals	

Even the least viscous oil C has a volatility one-tenth that of petroleum oil 1010. More viscous oils evaporate even less readily. The volatility of the oils increases sharply with the temperature.

Figure 14 gives data on the volatility of petroleum and synthetic oils at various temperatures after a period of 6.5 hours. In oils A and B,



notable evaporation only begins at 185° to 190°, whereas petroleum oils are volatilized almost completely at 205° to 206°.

Table 21

**Synthetic Oil Flow Characteristics at Low Temperatures**

Oil	Viscosity at 98.9°, in centistokes	Minimum oil circulation temperatures for viscosities of 5000 to 20000 centistokes
<b>Synthetic ester oil</b>		
A . . . . .	7.9	from -32 to -43
B . . . . .	3.6	" -48 to -67
C . . . . .	3.1	" -51 to -59
<b>Petroleum oil</b>		
1010 . . . . .	2.5	from -43 to -51
1100 . . . . .	20.5	" - 1 to -15

Table 22

**Volatility of Synthetic Oils**

Oil	Viscosity at 98.9° centistokes	Relative evaporation rate at 204°, based on evaporation rate of 1010 oil
<b>Synthetic ester oil</b>		
A . . . . .	7.9	2
B . . . . .	3.6	3
C . . . . .	3.1	10
<b>Petroleum</b>		
1010 . . . . .	2.5	100
1100 . . . . .	20.5	1

The basic results of engine tests on oils in turbojet engines are given in Table 23.

The frictional components of the engine after operation on ester oils were in good condition. Oil consumption was slight, owing to the low volatility of synthetic oils. The amount of resinous and carbon deposits on engine parts in high temperature areas and in the filters of the oil system during the testing of all three types of diester oils was small. No traces of corrosion were detected on metal surfaces. Petroleum oil 1010, tested under the same conditions, gave poorer results. The physical, chemical and operational characteristics of oil 1010 are given in greater detail in a preceding section.

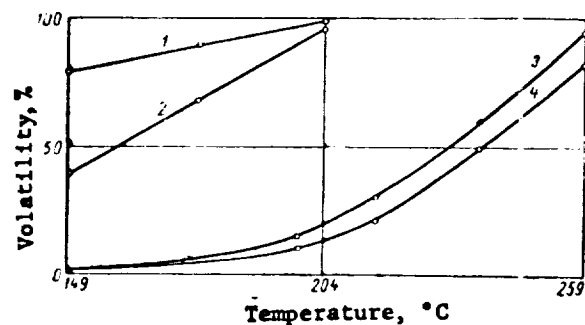


Fig. 14. Influence of temperature on volatility of synthetic and petroleum oils.

1 - petroleum oil 1005; 2 - petroleum oil 1010;  
3 - synthetic oil C; 4 - synthetic oil A.

Table 23

Results of Tests on Lubricating oils in Turbojet Engines

Indices	Petroleum oil 1010	Synthetic oils		
		A	B	C
Viscosity at 98.9°, centistokes	2.5	7.9	3.6	3.1
Lubrication of gears and bearings	Some scoring and wear	Exceptionally good	Good	Acceptable
Oil consumption	High to excessive	S l i g h t		
Carbon and resinous deposits	Medium to high	Slight to medium	Slight to medium	
Corrosion	No traces	No corrosion detected		
Circulation facility limits through oil system	From -40 to -50	-40	From -45 to -54	From -45 to -54

Tests demonstrated the considerable superiority of diester oils over petroleum oils and their suitability for work under all turbojet engine operating conditions. Oil A permitted starting of the engine at a temperature of -43° and oils B and C at temperatures of -45 to -54°.

Results of tests of diester oils on turboprop engines are given in Table 24.

**Table 24**

**Results of Tests on Lubricating Ester Oils in Turbojet Engines**

Indices	Petroleum oil		Ester oil	
	1100	Oil M, of MiL-0-6086 specifications	A	B
Viscosity at 98.9°, centistokes . . .	20.5	8.6	7.9	3.6
Maximum allowable load on gear transmissions, as % of load using 1100 oil. . . . .	100	-	105	50
Gear and bearing lubrication. . . . .	Good	Good	Good	Slight scoring
Oil consumption . . . . .	Slight	Slight	Slight	Slight
Carbon and resinous deposits. . . . .	Medium to large amounts	Large amounts	Slight to med- ium amounts	
Corrosion . . . . .	No traces noted	Some traces	None	
Minimum circulation temperature in oil system, °C . . . . .	-1	-	-40	-

Synthetic oil A fully permitted normal operation of all frictional components of the engine, including the shaft reducer. When oil B was used in strenuous operating conditions there were cases of scoring of gear teeth, indicating that its anti-wear properties were inadequate. Petroleum oil 1100, which was tested under the same conditions, was inferior to synthetic oils as regards resistance to the formation of carbon and resinous deposits and flow characteristics at low temperatures. More detailed specifications of oil 1100 have been given earlier. When mineral oil M was used, there was corrosion of certain metals at high temperatures.

Diester oils permit better operation of the hydraulic regulating mechanism of the engine at low temperatures. Tests on ester oils pointed to the need for improving the quality of the sealing materials used in the oil systems. The majority of normally used synthetic rubber gaskets rapidly disintegrated under the effect of ester oils during high temperature operations, particularly when low viscosity oils were used. Accordingly, new types of synthetic rubber gaskets were created which were more resistant to ester oils and were designed for use at temperatures of 148 to 176 degrees.

Synthetic lubricating oils based on various aliphatic esters are manufactured by the Esso Company under the trademark of EATO (Esso Aviation Turbo Oil).

Table 25 lists the basic physical and chemical properties of EATO ester oils, which are widely used on many British and American engines /55,56, 57/.

**Table 25**  
**Physical and Chemical Properties of EATO Ester Oils**

Indices	Synthetic oil				Petroleum oil	
	EATO-35	EATO-15	EATO-P.16 (Grade A)	EATO-P.13 (Grade B)	1010	1100
Viscosity, in centistokes, at temperatures in °C:						
98.9 . . . . .	7.5	3.6	3.8	3.3	2.5	20.5
37.8 . . . . .	38.0	14.0	-	-	10.0	about 249.3
-40 . . . . .	12 500	1600 to 1900	-	-	3000	-
-54 . . . . .	-	10500 to 12600	16000	12500	40000	-
Viscosity ratio:						
$v_{-40}/v_{98.9}$ . . . . .	1660	450	-	-	1200	-
$v_{-54}/v_{98.9}$ . . . . .	-	3208	4210	3788	16000	-
Solidification point, °C .	-51	-68	-59	-62	-57	Not a- bove 12.2
Flash point, °C . . . . .	232	221-232	221	210	145	250
Maximum load on gear teeth (on Ryder installation), kg per cm tooth width. .	576	360	378	332	32	576
Coking properties on metal surface at 315.6°, mg .	-	59	56	21	-	-
Oxidation stability and corrosion at 175°:						
Tolerated acid number increases . . . . .	-	+0.8	1.6	1.6	Not stable	
Tolerated viscosity va- riations at 37.8°C, % .	-	+2.0	5.7	5.7	Corrodes	
Weight variation, mg/cm <sup>2</sup> for steel, silver, al- uminum and magnesium, not more than. . . . .	-	±0.2	±0.2	±0.2	-	-
Weight variation, mg/cm <sup>2</sup> for copper, not more than. . . . .	-	±0.4	±0.4	±0.4	-	-
Corrosion at 232°, weight loss, mg/cm <sup>2</sup>						
for copper . . . . .	-	0.248	0.170	0.390	-	-
for silver . . . . .	-	0.11	0.465	0.420	-	-
Rubber swelling, % . . . .	-	-	21	37	-	-

For purposes of comparison certain constants of petroleum oils 1010 and 1100 are also given. Apparently, the synthetic oils under consideration consist essentially of octyl, nonyl and certain other esters of adipic, sebacic and other acids with admixtures improving their lubricating and antioxidant properties. Viscous polymetacrylate, having a high molecular weight, as well as other types of admixtures may be used in the production of more viscous oils.

Ester oils are superior to petroleum lubricating oils as regards all physical and chemical characteristics. In the case of all ester oils except EATO-35, the ratio of viscosities at  $-40^{\circ}$  and  $-54^{\circ}$  to those at  $98.9^{\circ}$  is substantially lower than that of petroleum oil 1010, indicating that these oils have better operating properties at low temperatures. Even EATO-35 oil which has a much higher viscosity at  $98.9^{\circ}$ , is very similar to oil 1010 in respect to this index.

In spite of their low viscosity at  $98.9^{\circ}$ , all synthetic oils have high maximum load values as measured on the gear teeth of the Ryder machine, thereby showing that they have good anti-wear properties. The oxidation stability of EATO oils is considerably better than for petroleum oils 1010 and 1100.

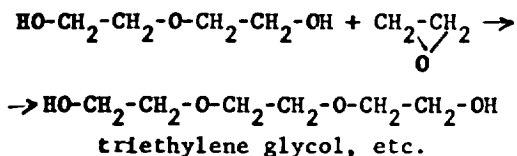
From the graphs in Figure 15 it will be seen that both basic synthetic oils EATO-15 and EATO-35 have very low vapor tensions, many times smaller than that of petroleum oils 1010 and RD 2490.

Ester oil EATO-15 permits normal operation of all types of turbojet engines. However, owing to its inadequate anti-wear properties it was found suitable for use only on some turboprop engines. Engines may be started with this oil at temperatures down to  $-55^{\circ}$ . Of all the ester oils, only EATO-35, with the best anti-wear properties, will permit operation of the frictional assemblies of all types of turbojet and turboprop engines. Because it has higher viscosity at low temperatures EATO-35 oil has poorer starting properties. Both EATO-P.16 and EATO-P.13 differ from the other types of EATO oils in having poorer stability at  $175^{\circ}$  and greater corrosiveness at  $232^{\circ}$ . Moreover, EATO-P.13 (grade B) oil produces rubber swelling. This type of oil is produced by reprocessing more readily available petroleum products and is intended for engines with less stringent lubricating oil requirements.

The specifications for EATO-P.16 and EATO-P.13 oils also include oil tests in humid vessels for periods of not less than 144 hours. Testing of ester oils in a humid vessel has been introduced as a result of the fact that some synthetic oils are subject to decomposition (hydrolysis) under the effect of water.

The raw materials for aliphatic esters needed in the production of synthetic lubricating oils may be petroleum products, natural hydrocarbon gas, certain vegetable and animal fats, turpentine, as well as other substances. Adipic acid may, for instance, be obtained from benzene and cyclohexane. Many alcohols needed for the synthesis of ester oils are synthesized industrially from carbon monoxide, hydrogen and unsaturated hydrocarbons which are obtained in large quantities during the reprocessing of petroleum.





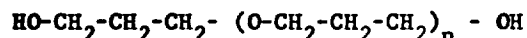
Products with molecular weights of 200 to 1000 are transparent, colorless liquids; the high molecular weight polymers are solids. Table 26 lists some of the properties of polyethylene glycols and polypropylene glycols.

Table 26

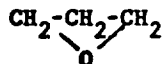
Properties of Polyethylene- and Polypropylene glycols

Compound	Solidification point, °C	Specific gravity, $d_{20}^{20}$	Viscosity at 98.9°C, centistokes
<b>Polyethylene glycols with molecular weights of:</b>			
190-210. . . . .	-	1.12	4
285-315. . . . .	-8 to -15	1.13	5
380-420. . . . .	4 - 10	1.13	7
570-630. . . . .	20 - 25	1.13	10
<b>Polypropyleneglycols with molecular weights of:</b>			
400-450. . . . .	-60	1.01	4
975-1075 . . . . .	-50	1.01	11
1950-2100 . . . . .	-45	1.01	24

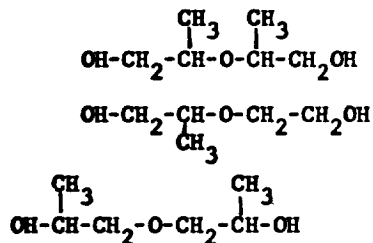
Polypropylene glycols have the following general formula:



Propylene glycol polymers are obtained through the condensation of propylene oxide

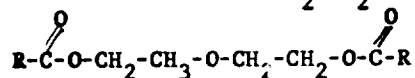


Polypropylene glycols may have side methyl groups. Thus, dipropylene glycol has three isomers with different arrangements of side methyl groups, as follows:



From the data in Table 26 it will be seen that the solidification point of polypropylene glycols is considerably lower than that of polyethylene glycols. This may be explained by the presence in polypropylene glycols of side methyl groups.

More valuable for obtaining synthetic lubricating oils are the polyglycol esters which are produced by the introduction of alkyl ester groups instead of hydroxyls at the ends of the polyglycol molecule. For instance, diethylene glycol may yield ethers having a structure of  $R-O-CH_2-CH_2-O-CH_2-CH_2-OR$  or esters with the structure of



Etherification of polyglycols makes it possible to introduce radicals of different size and structure into the glycol molecules, and thus to alter the properties of the final product in the desired manner. As compared to polyglycols which have retained the hydroxyl groups, polyalkylene esters have more favorable viscosity-temperature characteristics and other properties.

Table 27 lists the viscosities and solidification points of certain polyglycols, including those produced industrially. Similar data are given on turbojet engine lubricating oil 1010 for the purpose of comparison.

Table 27

**Physical and Chemical Properties of Polyglycols and Their Ethers**

Composition	Viscosity, centistokes, at temperatures of:				Flash point, °C	Solidification point, °C
	-40°	-18°	38°	99°		
Polyoxyisopropylene (DLB-B-50BX) . . . . .	905	109	8.0	2.5	177	Below -57
Polyoxyisopropylene (DLB-65-B) . . . . .	1950	190	11.8	3.2	193	" -54
Polyoxyisopropylene (DLB-130-BX) . . . . .	13000	750	28.4	6.5	252	" -54
Polyoxyisopropylene . . . . .	-	4000	65.0	11.0	254	-40
Dipropylene glycol pelargonate . . . . .	-	125	9.5	2.7	-	-34
Polyoxyisopropylene diether . . . . .	1000	120	9.4	2.9	188	Below -54
Polyoxyisopropylene diether . . . . .	-	-	70.8	12.6	241	-48
Petroleum oil 1010 . . . . .	3000	-	10.0	2.5	145	-57

As will be seen, polyglycol products have low solidification points and good viscosity-temperature characteristics. All polyglycol liquids have higher flash points than petroleum oils.

Table 28 lists some of the comparative characteristics of various lubricating oils for gas turbine engines. Both synthetic oils contain admixtures improving their operational properties. As regards volatility, polyglycol lubricating oil is considerably better than petroleum oils but is inferior to aliphatic diether oil.

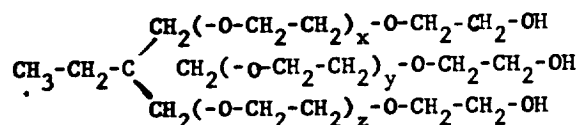


**Table 28**  
**Gas Turbine Engine Oil Properties**

Indices	Polyglycol oil (with admixtures)	Aliphatic diester oil (with admixtures)	Mixture of petroleum oils 1005 and 1010
Viscosity, centistokes, at temperatures in °C of:			
37.8 . . . . .	10.65	12.77	7.42
98.9 . . . . .	3.19	3.35	2.05
Flash point, °C . . . . .	182	218	127
Evaporation losses during 6.5 hours at 204°, weight % . . . . .	31	9	97

In Germany during the Second World War, experimental lubricating oils of the polyglycol ester type were prepared by ethoxylating polyatomic alcohols. Ethoxylation is the reaction involving the annexation of R-O- groups by alkoxyl alcohols. Alkoxyl group names are derived from the names of hydrocarbon radicals. According to this, CH<sub>3</sub>-O- is called methoxyl and C<sub>2</sub>H<sub>5</sub>-O- is called ethoxyl.

The lubricating oil manufactured in Germany under the name of LK-200 was obtained through the attachment of approximately 20 molecules of methylene oxide to one molecule of trimethylol propane /42/. The structural formula of the product was as follows:



A lubricating oil of this structure has great viscosity and a very high viscosity index. A characteristic feature of this product is its good solubility in water in all ratios and its insolubility in hydrocarbon liquids. This is due to the presence of three hydroxyl groups at the molecule endings. Esterification of hydroxyls results in the formation of products completely soluble in hydrocarbons but which will no longer readily dissolve in water.

The above mentioned synthetic oil was engine-tested on the special BMW 132 N engine. The tests showed that the oil had excellent lubricating properties, good stability and did not cause burning of the piston rings.

Table 29 lists some of the physical and chemical indices of an experimental ethoxylated oil produced in Germany.

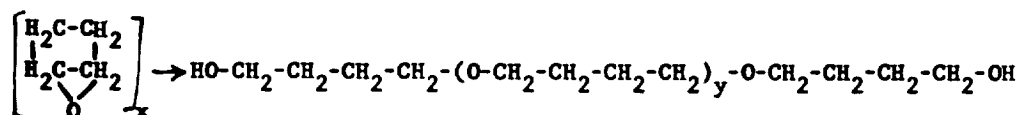
For the purpose of comparison, Table 29 also lists the constants of aviation lubricating oil MC-14 /29/ which is close to synthetic oil LK-2200 in respect to viscosity. Of special note are the high specific gravity, the high flash point and the very large coking number of the synthetic oil.

Table 29

## Properties of Ethoxylated Synthetic Oil

Indices	LK-2200	MC-14
Specific gravity $d_4^{20}$ . . . . .	1.119	0.890
Viscosity, centistokes, at temperatures in °C, of:		
37.8 . . . . .	117	-
98.9 . . . . .	13.9	14
Viscosity index . . . . .	117	-
Solidification point, °C . . . . .	- 38	- 30
Flash point, °C . . . . .	307	200
Ignition point, °C . . . . .	345	-
Acid number, mg KOH, . . . . .	0.51	0.25
Coke, according to Conradson, % . . . . .	1.17	0.45

Polyester synthetic lubricating oils containing alkoxins were also produced in Germany by reacting tetrahydrofuran and ethylene oxide. The splitting of the tetrahydrofuran ring and the ensuing polymerization resulted in the formation of polyether alcohols:



The products resulting undergo esterification which makes them soluble in hydrocarbon oils and lowers their solidification point.

Table 30 lists the properties of these oils.

Table 30

## Properties of Tetrahydrofuran Polyester Oils

Indices	Product 586	Product 620
Specific gravity $d_4^{20}$ . . . . .	1.014	1.024
Viscosity, centistokes, at temperatures in °C, of:		
37.8 . . . . .	98	406
98.9 . . . . .	16.4	55.3
Viscosity index . . . . .	over 140	over 120
Flash point, °C . . . . .	262	-
Solidification point . . . . .	-10	-15
Coke, according to Conradson, % . . . . .	-	0.2

While it has very high viscosity, product 620 has a comparatively low solidification point and its coking number is small. Polyalkylene glycol liquids have been fairly widely applied as lubricating oils for internal combustion engines, gear transmissions, compressors, vacuum pumps, as well as transfer agents, hydraulic liquids, etc. Results of the study of properties of polyalkylene glycol liquids and experience in using them as lubricating oils and working liquids have shown that it is possible to select lubricating oils among them, having good viscosity-temperature characteristics, satisfactory oxidation resistance at temperatures from 204° to 316° and good anti-wear properties. The favorable properties of polyalkylene glycol oils also include a lower volatility as compared to petroleum oils, low corrosive activity upon metals and good resistance to the effect of water. High heat resistance makes it possible to use polyglycols as liquid heat transfer agents subjected over long periods to temperatures of 232-260° without oxygen. In cases of insufficient oxidation resistance the stability of polyglycol oils may be improved by the addition of antioxidants.

Many authors have pointed out that when polyglycol esters are oxidized at high temperatures, low molecular weight volatile compounds and products readily soluble in oil are obtained. In such cases, there are none of the sediments which normally form during oxidation of petroleum oils, and choke the oil system with resinous and carbon deposits. The favorable properties of polyalkylene glycols likewise include inertness to natural and synthetic rubber sealing materials.

The synthetic lubricating oil industry based on polyethylene glycol compounds has adequate raw material resource to draw upon. The basic products are the unsaturated gaseous hydrocarbons (ethylene and propylene) which may be obtained in large quantities from natural hydrocarbon gas and the industrial gases of petroleum oil processing plants /26, 30, 33, 34, 46, 50, 51, 52, 58, 59, 60/.

#### Oils Based on Organic Silicates

Organic compounds containing silicon have acquired considerable practical importance in the last few years. The distinguishing properties of many silicon organic products are: stability at high temperatures, resistance to oxidation and the effect of humidity, good viscosity-temperature characteristics.

At present silicon organic compounds are the source of industrially produced rubber having exceptional resistance to heat and cold; resins for heat-resistant lacquers; hydraulic and other working liquids with viscosities not varying appreciably with temperature and permitting proper functioning of machinery at temperatures down to -70°; lubricating oils and greases with high heat resistance, as well as a number of other products.

Silicon organic compounds are in the forefront among synthetic liquids as regards viscosity-temperature characteristics, as may be seen from the character of the viscosity-temperature variation curves in Figure 16. Among all the products mentioned, those with the most unfavorable viscosity characteristics are the organic fluorides.

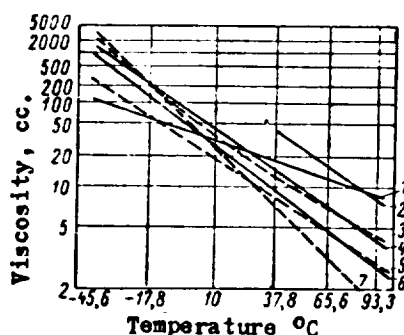


Figure 16. Viscosity-temperature relationship in synthetic oils.

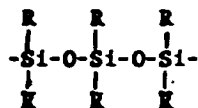
1 - dimethylsilicone: v.i. 200; 2 - Pennsylvania oil: v.i.=104; 3 - polyalkylene glycol derivative: v.i.=177; 4 - di-2-ethylhexylsebacate: v.i.=175; 5 - tetraoctylsilicate: v.i.=175; 6 - trioctylphosphate: v.i.=94; 7 - trifluorovinylchloride polymer.

The good heat resistance of some of the silicon organic compounds makes it possible to use them as heat transfer agents during prolonged operations at 350°. Researchers looking for synthetic gas turbine engine lubricating oils stable at high temperatures are paying considerable attention to organic silicates. Large-scale research conducted over the past few years by Soviet scientists and those abroad has given rise to the extensive chemistry of silicon organic compounds.

As regards physical and chemical properties, the most interesting compounds for obtaining heat resistant lubricating oils are those falling within the organosiloxane and orthosilicic acid ester class.

#### Organosiloxanes

Organosiloxane compounds, also known under the technical names of silicons, consist of consecutively bound atoms of silicon and oxygen:



R designates an organic radical or any atomic group.

The combination of  $-\text{Si}-\text{O}-\text{Si}-$  atoms is called the siloxane group.

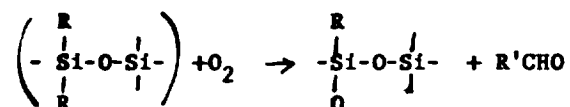
Compounds having a large number of organosiloxane groups are called polyorganosiloxanes.

Polyorganosiloxanes may have linear, cyclic or spacial molecular structures. The silicon-oxygen group  $-\text{Si}-\text{O}-$  is highly heat resistant, much more so than the C-C and the Si-C groups. That is why silicon organic polymers with a siloxane group have a higher heat and oxygen resistance than organic compounds forming part of common petroleum oils containing essentially the  $-\text{C}-\text{C}-$  group.

The heat resistance of the  $-\text{Si}-\text{O}-\text{Si}-$  group is largely dependent upon the number of organic radicals or groups bound to the silicon, their structure and the structure of the organic silicate molecule as a whole.

With an increase in the number of organic radicals bound to silicon the heat resistance of the siloxane group falls off. A strong influence in raising the heat resisting properties of polyorganosiloxanes is exerted by the phenyl group. For instance, certain polydimethylsiloxane liquids are stable only up to 175°, whereas polyphenyldimethylsiloxanes are resistant up to 250°. Organosiloxanes oxidize differently from organic compounds. For instance, paraffin hydrocarbons begin to oxidize in an air stream at a temperature slightly above 100°, with disruption of the  $-\text{C}-\text{C}-$  combination in the

side groups and in the basic chains of the molecule. As a result, access of oxygen to the yet unaffected chains is increased, and the oxidation process develops at an accelerated rate. Polyorganosiloxanes begin to oxidize only at 180 to 200° with disruption only of the  $-\text{Si}-\text{C}-$  group of organic radicals in the side chains. The resulting volatile products of oxidation consist essentially of carbon monoxide, carbon dioxide, aldehydes and other compounds. In those parts of the basic chain of the molecule where oxidation of an organic radical has occurred, additional siloxane groups are created, thus:



This rearrangement of the molecule hampers oxygen access to the unaffected organic radicals, and further oxidation of the compound is slowed down. Oxidation is strongly resisted by cyclic and spatial molecular structures. Figure 17 represents models of molecular structures of polyorganosiloxanes. In certain polyorganosiloxanes having a spatial structure the bonds are disrupted at temperatures above 500°. Organic silicate polymer organosiloxane products used as lubricating oils and hydraulic liquids are transparent odorless liquids. They are chemically inert and have a high heating and oxidation stability. The viscosity, boiling and freezing points, as well as the other physical and chemical properties of polyorganosiloxane liquids, which depend upon molecule size and structure, vary within very wide limits. Table 31 lists the properties of some polysiloxane liquids.

A study was made of the physical properties of linear liquid polymers with chains containing from 24 to 356 atoms of silicon. Polymethylsiloxanes

are normal liquids with a very low degree of association.

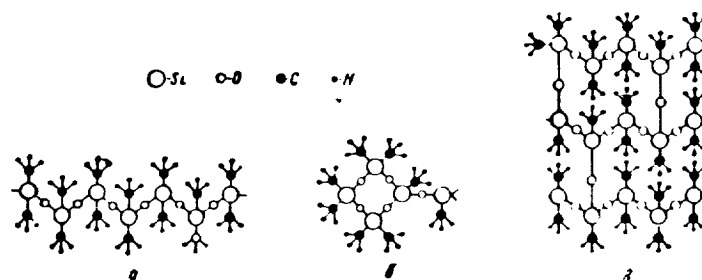


Fig. 17. Models of molecular structures of polyorgano-siloxane liquids.

a - linear molecule structure; b - cyclic molecule structure; c - spatial molecule structure.

Table 31

Properties of Polysiloxane Liquids

Viscosity at 25°, centistokes	Solidification point, °C	Boiling point at 0.5 mm, °C	Flash point, °C	Specific gravity at 25°
Polymethylsiloxane liquids				
5.0	-70	120-160	132.2	0.918
10.0	-67	200	176.7	0.940
20.0	-60	220	271.7	0.950
50.0	-55	250	232.2	0.955
Polyethylsiloxane liquids				
10.2	below -110	150-237 (at 8 mm)	110	0.983
87.4	-94	200-282 (at 8 mm)	153	-

Figure 18 shows the viscosity-temperature relationship for various polymethylsiloxane liquids and petroleum oils. It will be seen from Figure 18 that organic silicon liquids have a considerably better viscosity-temperature characteristic than petroleum oils with the same viscosity. The viscosity of polymethylsiloxane and petroleum oils with the same viscosity. The viscosity of polymethylsiloxane and petroleum oil is the same at 100°. When the liquids are cooled to -35°, the viscosity of the former increases by a factor of 7 and that of the latter by a factor of 1800. The viscosity of one of the silicone liquids ( $v_{37.8} = 39.8$  centistokes), which is four times that of mineral oil 1010, is 668 centistokes at -54°, i.e. about 1-1/2% of the 1010 oil viscosity. Polymethylsiloxane liquids are considerably less volatile, solidify at lower

temperatures and have a higher flash point than petroleum oils of the same viscosity.

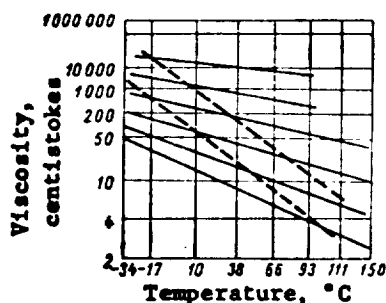


Fig. 18. Viscosity-temperature relationship in polymethylsiloxane liquids and petroleum oils.

polymethylsiloxane liquids;  
petroleum oils.

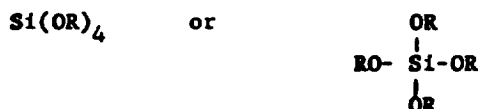
Polyalkylarylsiloxane liquids having mixed alkyl and aryl (aromatic) radicals, are used on a large scale as hydraulic liquids, lubricating oils and ingredients in the preparation of consistent greases and other products. K. A. Andrianov states /61/ that these compounds do not change color in the presence of air oxygen at temperatures up to 250°. The stability of polyalkylarylsiloxane oils may be improved by the addition of inhibitors. Oils containing an inhibitor will be inert with respect to copper, bronze, brass, aluminum, magnesium, iron, steel, tin, lead, cadmium and chromium when heated up to 150° and are themselves unaltered under the effect of these metals.

Some authors state that at high temperatures polysiloxane liquids have a tendency to form gel-like deposits, a feature to be taken into account in the examination of the properties of siloxane oils. The anti-wear properties of silicone oils which depend on their structure, have not yet been sufficiently studied. Some data are provided /26/ on the poor lubricating properties of polysiloxanes in cases of sliding friction of steel upon steel. During oil tests on a four-ball machine, ethylpolysiloxane oil was found to be inferior to MS-20 oil as regards the diameter of the wearing trace in the loading area prior to the removal of the oil film, and as regards the magnitude of the critical load  $P_K$  at which removal of the oil film occurs. The anti-wear properties of methylpolysiloxanes are somewhat inferior to those of ethylpolysiloxanes. According to other sources /62/, heat resistant silicone lubricating oil F-50 for jet aviation, which does not contain any additive, has good lubricating properties. F-50 oil permitted proper functioning of bearings at temperatures from 200° down to -75°. Variation in the oil viscosity was smaller than in the case of other oils. Another silicon organic oil /63/ was stable at temperatures up to 260° and showed good lubricating

properties during tests on bearings with loads up to 75 kg/cm<sup>2</sup>.

### Silicic Acid Esters

Among the organic silicates there is a large group consisting of organic esters of orthosilicic acid. The structural formula of orthosilicates is as follows

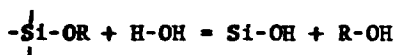


where R is the same or different groups.

The properties of orthosilicates are governed by the presence of reactive  $\begin{array}{c} | \\ \text{-Si-O-C-} \\ | \end{array}$  groups. One, two or three  $\begin{array}{c} | \\ \text{-O-C-} \\ | \end{array}$  alkoxy groups in an ester molecule may be replaced by organic radicals. The resulting compounds are substituted orthosilicic acid esters:

- 1) monosubstituted  $\text{-R-Si(OR')}_3$ ;
- 2) disubstituted  $\text{-R}_2\text{-Si(OR')}_2$ ;
- 3) trisubstituted  $\text{-R}_3\text{-Si(OR')}$ .

Orthosilicic acid esters can be hydrolyzed, i.e. an alkoxy group may be detached under the effect of water and particularly of alkalis:



The intensity of this reaction will depend upon the structure of the ester. The hydrolysis of orthosilicic acid esters leads to the formation of gelatinous polymer products or gels, a matter which must be borne in mind during tests and in the application of these compounds as lubricating oils.

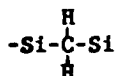
Information on the properties of silicic acid esters is given in works on the study of gas turbine engine lubricating oils. These products have excellent viscosity-temperature characteristics and good mobility at low temperatures, low volatility and low inflammability. In addition, oils of this type will not corrode most metals and have quite satisfactory lubricating properties permitting reliable functioning of bearings and gear transmissions.

A serious drawback of silicate-based oils is their poor stability at high temperatures and the tendency to decompose under the effect of water, and to form gels and abrasive silicon dioxide  $\text{SiO}_2$ . The inclination of esters to hydrolyze depends upon their structure. Substituted esters in which one, two or three alkoxy groups have been substituted for organic radicals will not hydrolyze as readily. For instance, diphenyldiphenoxysilane  $(\text{C}_6\text{H}_5)_2\text{-Si-(OC}_6\text{H}_5)_2$  is very stable in the presence, not only of water, but also of weak alkaline solutions. According to certain other information, some other organic silicates are highly heat resistant.



Moreton states /52/ that prolonged testing silicate-based synthetic oils containing oxidation retarders at temperatures of 204° to 260° gave good results. Resistance to hydrolysis in esters may be improved by the addition of suitable admixtures to the oils. Organic silicate esters absorb well additives improving the stability and the lubricating properties of petroleum oils. Silicic acid esters are being used as liquid heat transfer agents, high temperature hydraulic liquids and low viscosity consistent greases.

Apart from the classes of organic silicates considered above, increasing attention has been devoted in recent times to the synthesis and study of properties of compounds in the siliceous hydrocarbon category containing the following groups

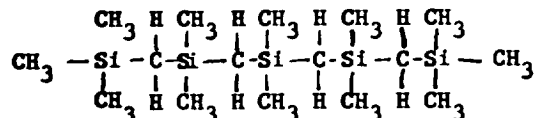


The methyl groups  $-\text{CH}_2-$  connected to siliceum atoms are noted for their thermal and hydraulic stability, a feature which raises the stability of the compound as a whole. The  $\text{>Si-CH}_2\text{-Si>}$  groups may be introduced into polymer organosiloxane compounds as well, in order to impart useful new properties to them.

Siliceous hydrocarbons differ from ordinary hydrocarbons in having good oxidation stability at high temperatures and a lower solidification point.

A. D. Petrov and V. S. Chugunov /39/ obtained liquid siliceous hydrocarbons with one and two naphthyl radicals, some of which solidified at -40°. They did not decompose on distillation at 350-400°.

Polymers of the following type:



which were recommended as lubricating oils and hydraulic liquids, solidified at temperatures below -95° /64/.

The viscosity of siliceous hydrocarbons is greater than that of polyorganosiloxanes with molecules of the same size. However, the viscosity-temperature variations follow a steeper curve /26, 39, 51, 61, 65/.

#### Organic Phosphates and Halogen Compounds

The increasingly stringent requirements for gas turbine engine lubricating oils, particularly as regards resistance to oxidation under heat, are inducing researchers looking for high quality oils, to study the properties of still other types of organic compounds. Among these, considerable attention is being given to organic phosphoric acid esters, and chlorinated and fluorinated organic compounds. From the literature, it is known that many of the organic phosphate liquids that have been examined, have excellent anti-wear properties, low inflammability and low volatility. Some of the products considered have satisfactory and, in certain instances, good viscosity-temperature properties. Examination of the stability of liquid organic phosphates

shows that they resist oxidation at temperatures up to 150° but are not sufficiently stable at higher temperatures, a feature which prevents their being used as lubricating oils for gas turbine engines.

As was shown above, typical liquid organic phosphates have the highest coking number, (about 480 mg), obtained during the determination of coking properties on a metal plate at 315.6° for 8 hours. As regards resistance to hydrolysis, these compounds are intermediate between aliphatic diesters and silicic acid esters. Liquid organic phosphates cause undue swelling of various types of rubber, but this may be prevented by altering the rubber composition.

The physical and chemical properties of organic compounds are very strongly affected by the introduction of fluorines into the molecule. Considerable attention was paid to fluorinated compounds during the Second World War in connection with the utilization of atomic energy, where the need arose for highly stable lubricating products.

Fluorination of hydrocarbons produces compounds in which the atoms of hydrogen are replaced by fluorine. When all the hydrogen atoms are replaced, the hydrocarbon is transferred into a fluorocarbon. Normally, the prefix "perfluor" is added to the name of a fully fluorinated hydrocarbon. For instance, the compound  $\text{CF}_3-(\text{CF}_2)_6-\text{CF}_3$  is called perfluorooctane.

Perfluorocarbon oils are transparent liquids. The distinctive feature of perfluorocarbons is their exceedingly high chemical and thermal stability. At normal temperatures, they will not interact with such potent oxidizing agents as nitric acid, fuming sulfuric acid, chromic acid, etc. Hydrogen and alkalis will not act upon fluorocarbons even at high temperatures. Fluorocarbons are unaffected by oxygen, will not burn and will not decompose at temperatures up to 400 and 500°.

The unfavorable properties of fluorocarbon liquids include a very sharp increase in viscosity with temperature drops, and a very high solidification point. The temperatures range between the solidification and boiling points in fluorinated hydrocarbons is very narrow. Figure 16 shows that even incompletely fluorinated compounds of trifluorovinyl chloride have very poor viscosity-temperature characteristics. The anti-wear properties of fluorocarbon oils are as good as those of petroleum oils. Fluorocarbon oils are used for the lubrication of machines and mechanisms operating at high temperatures in the presence of chemically active substances.

Because of their high stability to thermal oxidation, good anti-wear properties and low inflammability, chlorinated hydrocarbons are similar to fluorocarbons. However, they have the same unfavorable properties: a poor viscosity-temperature characteristic, a high solidification point, toxicity, etc., although these are less pronounced than in the case of fluorinated hydrocarbons.

In looking for lubricating oils for gas turbine engines, researchers try to use the favorable effect of fluorine and chlorine upon organic structures, so as to produce those properties, such as stability and the protection of frictional components from wear, which are required of lubricating oils.

Modern organic chemistry opens up great possibilities for the production of synthetic lubricating oils capable to a larger extent than existing oils, of fulfilling the requirements to be met by oils for aviation gas turbine engines /22, 26, 33, 34, 39, 66/.

## Chapter V

### OIL TESTING METHODS

The properties of aircraft gas turbine engine lubricating oils are studied and their qualities are evaluated for control purposes, on the basis of the majority of the customary, well-known methods used for engine oils. These include methods for determining viscosity, solidification point, flash point, ignition point, acid number and the other physical and chemical properties. The methods of evaluating the quality of piston engine oils will not in every case yield indices accurately defining the behavior of oils in turbojet and turboprop engines. Considerable attention has been devoted recently to the development of methods for determining the oxidation stability, antiwear, corrosive and other properties of oils which would produce results agreeing more closely with their behavior in jet engines. Only special methods of testing gas turbine engine oils that have been already applied in laboratories, and certain general methods of examining engine oils that are of particular interest for the present purpose, will be considered hereinafter.

#### Oxidation Stability of Oils at High Temperatures

The oxidation stability of gas turbine engine oils may be studied by using oxidation by air or oxygen based on the replacement of the oxygen used up in oxidation /8, 24, 26, 31/. The All-Union Heat Engineering Institute (VTI) method which has become widespread throughout the USSR (GOST\*981-4) and which was developed for evaluating the stability of transformer and turbine oils /67/, is used in a modified form in testing gas turbine engine oils. According to the standard procedure, 30 grams of oil are poured into a cylindrical glass vessel. At 140°, in the presence of catalysts (a copper or iron ball), air is pumped through the oil for 14 hours at the rate of 50 milliliters a minute. To assimilate the VTI method to the oil's working conditions in a gas turbine engine, the experimental temperature is raised to 150-175° and in certain instances to 200°. Depending upon the type of oil and its purpose, the set oxidation time may vary from 10 to 50 hours. In certain cases, instead of metal balls, metal plates of steel, aluminum and other alloys with which the oil comes in contact in the oil system of engines are introduced. Once the oil is oxidized, the acid number and the sediment which is insoluble in refined benzine (60-120° fraction), benzene and other solvents, are determined. In the oxidation of synthetic as well as petroleum oils containing non-hydrocarbon components, the selection of the solvent for

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\*GOST: All Union State Standard

determining the sediment in the oxidized oil is of considerable importance.

#### Coking on an Aluminum Plate

This method provides an evaluation of the tendency of oils to form hydrocarbon deposits on the engine's metal components when raised to high temperatures.

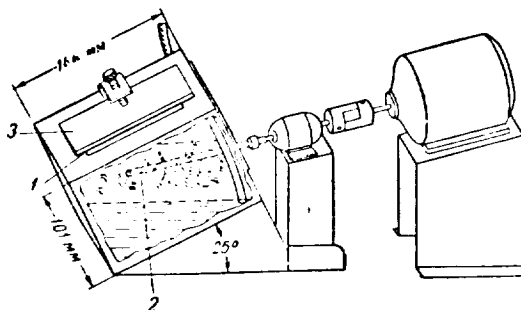


Fig. 19. Diagram of apparatus for determining the coking properties of oils.

1 - aluminum plate; 2 - rotating oil sprayer;  
3 - electric plate heater.

The method was developed in the United States /22,34,35,55,56/. As may be seen from a sketch of the apparatus (Fig. 19), the oil reservoir contains a shaft with a metal comb consisting of eight rows of teeth. The oil reservoir is positioned at an angle of  $25^\circ$  to the horizontal. The oil from the cylinder is poured into the reservoir to a level somewhat below that of the shaft. The teeth of the shaft comb are partially immersed in the oil. During the test the shaft is rotated at a speed of  $1000 \pm 50$  rpm. As the oil is sprayed, it falls upon the aluminum plate located above. The temperature of the plate is maintained by means of an electric heater located upon it. The duration of the test is 8 hours and the temperature is  $315.6^\circ$ . The coking property of the oil is determined by the weight of hydrocarbon deposits formed on the aluminum plate.

#### Oil Tests on Roller Bearings

Tests of oils for stability on roller bearing installations at high temperatures and high rotational speeds are conducted in the U.S.A. and Britain under near-operating conditions/22,35/. These tests also make it possible to check the oils' volatility, corrosive action on some of the bearing parts, and in certain instances their anti-wear properties. Tests on roller bearing installations have shown a fairly high degree of agreement with oil behavior in full-scale engines and have therefore recently found extensive application.

There are several types of installations of this kind. In Britain, the NAPIR installation is used, in which the ball bearings have an internal diameter of 50.8 mm and are operated at 21,000 rpm. The temperature during the

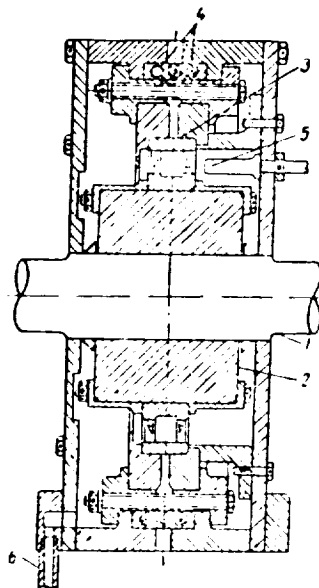


Fig. 20. Wright installation for testing oils on bearings at high temperatures.

1 - shaft; 2 - hub; 3 - tested bearing; 4 - electric heater; 5 - oil supply nozzle; 6 - oil outlet.

oil tests is maintained at 280° for 6.5 hours. 1420 ml of oil are circulated through the bearing per hour. Tests are repeated until a substantial amount of deposit which will prevent functioning of the bearing is formed or until the first indications of damage to the bearing appear.

In the United States, oil stability is determined on the Wright installation, which is equipped with a roller-bearing having an internal diameter of 127 mm rotating at 8300 rpm. The temperature of the outer casing of the bearing is maintained at 371° during the test. 227 g of oil are supplied to the bearing per hour. Maximum test duration is 7 hours. A diagram of the Wright installation is given in Figure 20. The external appearance of the bearings after the testing of three different types of oil is reproduced in Fig. 21. It may be seen that substantial carbon deposits were formed on the first bearing, as a result of this test. Tests of the two other stabler oils, on the second and third bearings, showed that carbon deposits were small, but that

large amounts of resinous deposits were formed on the second bearing.



Fig. 21. Bearings after testing with three different oils.

1 - Bearing has carbon deposits following test with unstable oil; 2 - resinous sediments have settled on the bearing; 3 - bearing is in satisfactory condition after test with stable oil.

#### Determination of Oxidation Resistance and Corrosiveness of Gas Turbine Engine Oils in Accordance with U.S. and British Technical Specifications

The official technical specifications for gas turbine engine lubricating oils include oxidation stability tests, with a simultaneous determination of the oils' corrosive activity, and separate tests for corrosive activity alone at high temperatures /55, 56, 57/. In the first method, the oils are oxidized at 175° in the presence of steel, silver, aluminum, magnesium and copper. After oxidation a determination is made of the acid number of the oil and the viscosity at 37.8°, as well as the variation in weight of all the metal plates, in mg/cm<sup>2</sup>. Corrosive activity tests are carried out on copper and silver at 232.2°. As usual, corrosive activity is determined on the basis of the change in weight of the plates, in mg/cm<sup>2</sup>.

Among the methods for determining an oil's oxidation stability based on the amount of oxygen used up in the oil oxidation, the AzNII (Azerbaijani Scientific Research Institute) method developed by A.M. Kuliev, A. M. Levshina and A. E. Blumstein /68/ deserves particular mention.

#### Determination of Oil Oxidation Stability on the Basis of the Amount of Oxygen Consumed - AzNII Method

A diagram of the apparatus is given in Figure 22. Oil bath 4 contains an attached, movable dish with two glass ampoules 5, provided with outlet tubes. The dish is oscillated by means of a small electric motor 6. Weighed amounts of oil from 20 to 50 g are poured into the ampoule which is connected 75 ml burettes 2. The burettes are water jacketed for temperature control. A three-way valve permits communication of the burettes with the atmosphere, a pressure regulating flask 1 and the oil ampoule. Before the

beginning of the test, the burettes are filled with water. To displace the air, oxygen is passed through the ampoule tube for 10 to 15 minutes, and is

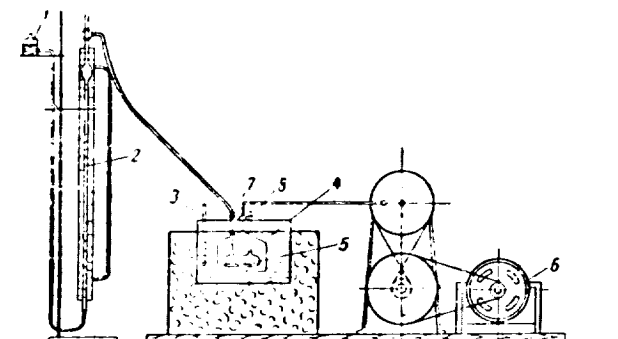


Fig. 22. Diagram of AzNII apparatus for determining oil stability.

1 - Pressure regulating jar; 2 - burette; 3 - thermometer; 4 - oil bath; 5 - ampoule with oil; 6 - motor; 7 and 8 - valves.

allowed to escape through the three-way valve. Both ampoules, without being disconnected from the burettes, are placed in the oil bath which has been heated to the test temperature. As a result of oxidation, oxygen is absorbed and the water in the burette rises. The time taken by the water to fill 1 ml of the burette is conventionally taken as the induction time for oil oxidation. Oxidation is terminated after 10 to 50 ml of oxygen have been absorbed. Oil stability indices are the oxidation induction period in minutes and the total amount of oxygen consumed, in ml. After the test, the oxidized oil may be analyzed. Good results were obtained by the AzNII method in tests of various engine lubricating oils and light compressor oils.

For a more detailed analysis of the oxidation of oil and of volatile products liberated during oxidation, P. P. Borisov has proposed the Moscow State University (MGU) method /69/. In this case, oxygen is circulated through the oil during the test and the amount of it used up in oxidation is periodically measured. The volatile products of oxidation of the oil are retained by absorbents.

#### Oxidation of Thin Layers of Oils

In order to determine the degree to which oils will oxidize in thin layers, use may be made of the method for determining oil resistance to oxidizing condensation as proposed by S. E. Krein and P. A. Lipshtein /70/.



The apparatus in this method is represented in Figure 23. 1 g of oil is poured into a flat-bottomed dish having a diameter of 70 mm. A layer of oil of approximately 0.4 mm is obtained. The dish containing the oil is placed

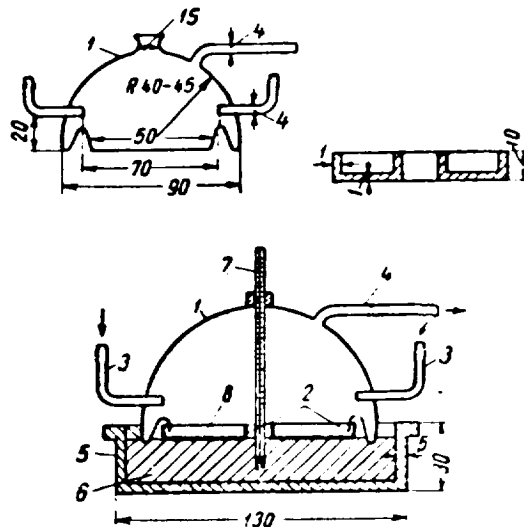


Fig. 23. Apparatus for determining oil stability with regard to anti-oxidant condensation.

1 - glass ball; 2 - aluminum cup; 3 - air inlet;  
4 - air outlet; 5 - thermostat; 6 - Wood's alloy;  
7 - thermomenter; 8 - oil.

into a bath filled with Wood's alloy heated to 250°, and is hermetically sealed within a glass bell. Dry air is admitted through a tube into the bell at the rate of 50 ml per minute for 3 hours. The residue after the oil has been oxidized is transferred to a filter paper container which is weighed and placed in a Soxhlet. Subsequent decomposition of the residue by means of petroleum ether, alcohol and benzene makes it possible to determine the amount of oil with neutral resins, as well as that of hydroxy acids and asphaltenes present. A determination is made of the acid number of the resulting products. The equipment in this experiment may also be used for determining oil oxidation by oxygen consumption. In that case, both air inlet tubes are connected to the burette which is filled with oxygen or air and the air outlet tube then closed.

### Anti-Wear Properties

A proper evaluation of the anti-wear properties of oils for modern turbojet and particularly turboprop engines is of primary importance in selecting new oils and in checking the quality of oils already in use. A method which is widely used in determining the anti-wear properties of gas turbine engine oils is the four-ball oil testing machine method, using a frictional machine with point contact of the frictional surfaces. Several types of four-ball machines are known in the Soviet Union /8, 70/. A method of oil testing using gear transmissions has recently been introduced.

#### Evaluation of the Anti-Wear Properties of Oils by the Four-Ball Machine

Figure 24 shows the layout of the frictional assembly of V. D. Zelenski's perfected four-ball machine /71/. The frictional assembly consists of a pyramid of four steel balls. The upper ball is tightened by a nut against the end of the shaft. The three lower balls placed in a cup of oil are tightened against the upper ball. The diameter of the balls during the experiment may be 5.92, 9.82, 12.7 and 19.05 mm. When balls with a diameter of 12.7 mm are used the amount of oil introduced into the cup is 3.7 ml. This amount may be reduced to 2.6 mm if the space between the balls is filled with suitably shaped filler. The design of the four-ball machine makes it possible to study the anti-wear properties of metals and oils in specific gaseous atmospheres. Purified gas (oxygen, nitrogen, etc.) is introduced into the oil along a tube inserted into the cup instead of the thermocouple. In such cases the frictional assembly is sealed off with a gasket.

The cup with the oil sample is placed in a double-walled thermostat, with water circulating between the walls to heat the frictional assembly to 95°. Electric heaters are used to produce higher temperatures. The specified temperature is regulated by a pyrometric millivoltmeter of the MPSH Pr-54 type, where the indicator is a chromel-copel thermocouple.

The frictional assembly is loaded by means of a hydraulic device capable of producing loads of 15 to 300 kg and of maintaining them at a constant level through the test. The engine shaft with the upper ball fixed to it is rotated by an electric motor by means of a hydraulic pump or a hydraulic motor. The friction produced during the wearing of the balls is recorded by a special automatic recorder. The amount of wear is determined by a microscope provided with an opacity illuminator on the basis of the diameter of the wear spots forming on the frictional surfaces of the lower balls in their contact area with the upper ball. The lubricating properties of oils determined on the four-ball machine are expressed most frequently in terms of the mean diameters of the wear spots for different loads. The results obtained are presented in the form of a diagram of the relationship of the diameter of wear spots to the load, plotted on log-log coordinates. The axial loads acting upon the balls are plotted along the abscissa and wear sizes are entered along the ordinate.

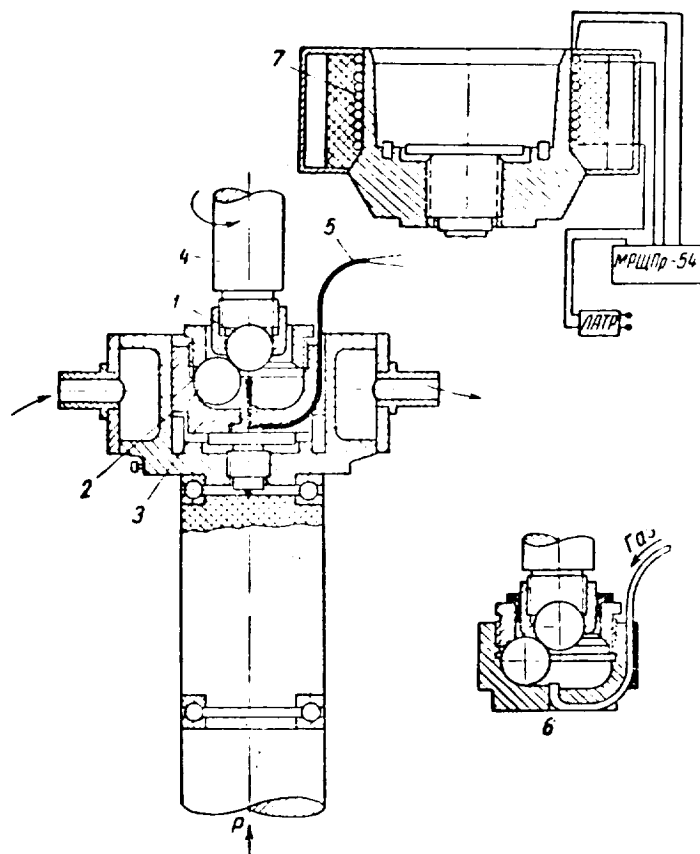


Fig. 24. Frictional assembly of four-ball machine.

1 - upper ball; 2 - 3 lower balls; 3 - cup with test oil;  
4 - shaft; 5 - thermocouple; 6 - gas supply to oil; 7 - electric  
heater for frictional assembly.

#### Oil Tests on Gear Transmission Machines

The evaluation of anti-wear and lubricating properties of oils for reducers and other gear transmissions on laboratory friction-measuring apparatus does not always agree with the behavior of the oils under operating conditions. That is why numerous oil tests are performed on machines involving frictional assemblies with toothed transmissions [72]. In the United States and Britain, special machines have been developed to study the anti-wear properties of gas turbine engine oils [22, 35, 73]. These machines incorporate full-scale geared transmissions of aircraft engines. The gear transmissions to be tested are mounted on two parallel shafts. Shaft loading is produced by hydraulic pressure. The installation is operated at 10,000 rpm

at a temperature of  $74^{\circ}$ . For each test, either a new set of gear wheels or a used one with trimmed teeth is utilized. The test consists of several 10-minute stages with tooth inspection after each stage. Tests are continued until surface wear on the teeth attains 22.5%. The test results are expressed in terms of the load in kilograms per centimeter of gear width for a given amount of wear of tooth surface. Normally, the average value of the results of two tests is taken.

### Oil Frothing

Frothing is determined by blowing thinly dispersed air through the oil or by ejecting a stream of oil into rarefied space.

#### Determination of Frothing by the Air Dispersion Method

This method has been developed by Y. G. Mamedaliev, A. M. Kuliev and L. S. Mustafaev /26/. A diagram of the apparatus is reproduced in Fig. 25.

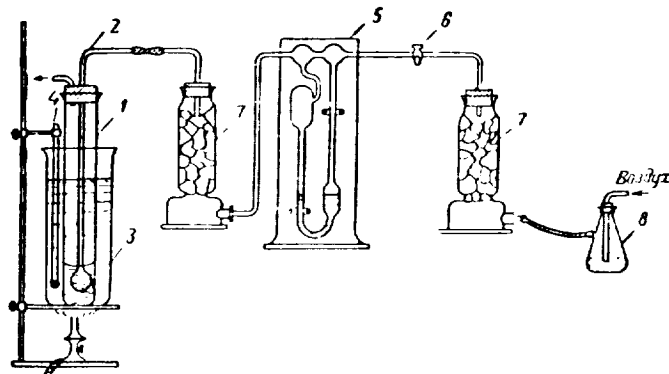


Fig. 25. Apparatus for determining frothing of lubricating oils.

1 - Graduated cylinder; 2 - air supply tube; 3 - glass vessel; 4 - thermometer; 5 - rheometer; 6 - 3-way valve; 7 - calcium chloride tube; 8 - jar with cotton-wool.

The apparatus consists of a 250 ml graduated cylinder 1 provided with a rubber stopper with two holes. One of these is an air inlet and holds a glass tube of 0.2 to 0.3 mm bore with a spherical bulb. The lower end of the tube should be at a distance of 2 to 3 mm from the bottom. An air outlet glass tube is inserted into the other hole. To maintain the required temperature, the cylinder is placed in a 500 ml jar containing a thermostatic liquid and a thermometer 4. 25 ml of test oil are poured into the cylinder and air is passed through it. At regular intervals, the volume of froth produced is measured.

### Determination of Froth by the Falling Stream Method

Oil frothing by the falling stream method is determined on apparatus developed by L. V. Zhirnova (Figure 26).

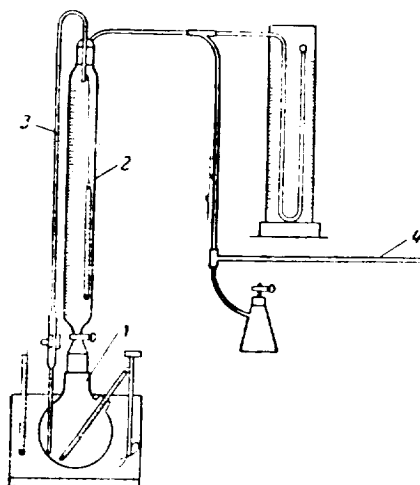


Fig. 26. Diagram of apparatus for determining oil frothing.

1 - flask; 2 - cylinder; 3 - tube for transferring oil from flask to cylinder; 4 - vacuum pump tube.

A 100 ml flask, into which the test oil is poured, is placed in a thermostat. A graduated cylinder 2 is connected to the neck of the flask by means of a valve. Frothing takes place in the cylinder. A glass tube extends from the bottom of the flask to the upper part of the cylinder. The tube is terminated by a capillary with a 0.5 mm bore. The polished glass stopper of the cylinder holds a second tube which connects the cylinder with a vacuum pump and a manometer. Before the test, the tube for transferring the oil from the flask to the cylinder is insulated with asbestos. 20 ml of test oil is poured into the flask. After that, the thermostat is turned on and the oil in the flask is heated to the required temperature. When this temperature is reached, the clamp on the side tube and the cylinder valve are closed. The required rarefaction is created in the cylinder by means of the vacuum pump. After a temperature check, the clamp on the side glass tube connecting the flask to the cylinder is suddenly opened. The oil rises in the tube and enters the cylinder through the capillary. On emerging from the capillary and coming into a rarefied atmosphere, the oil froths. When all the oil has passed into the cylinder, the height of the froth in the cylinder is read on the graduations. The temperature of the frothed oil is measured at the same time. After that the vacuum pump is turned off and the valve of the buffer

flask is opened to bring the pressure to that of the atmosphere. Simultaneously, a stop-watch is started and the time required for the froth to disintegrate is noted. The frothing coefficient of the oil is determined from the following equation:

$$K_{\text{froth}} = \frac{h_1}{h},$$

where  $h_1$  is the height of the column of froth in the cylinder and  $h$  is the height of the column of oil in the cylinder without froth.

An additional characteristic of the tendency of oils to froth is froth stability, expressed in seconds.

#### Determination of Oil Volatility

Oil volatility may be determined on the apparatus represented in Fig. 27. It consists of a 250 ml flask 2 and a graduated 100 ml cylinder 3 in which the oil's evaporated light fractions are collected. A glass tube of 5 to 10 mm diameter through which air from a blower is passed through the oil in the flask is inserted into the flask. The flask is placed in an oil-filled thermostat.

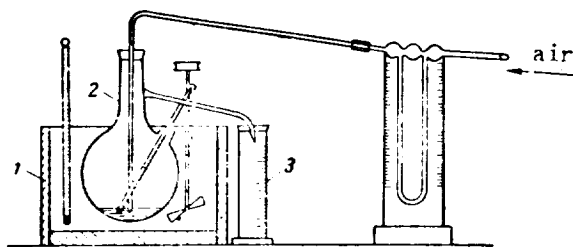


Fig. 27. Diagram of apparatus for determining oil volatility.

1 - thermostat; 2 - flask; 3 - cylinder.

Oil volatility is determined in the following manner. 100 g of test oil are poured into the flask. The end of the outlet tube is passed through the stopper and into the cylinder for collecting light fractions. When the required temperature is reached, the air supply is turned on and the time of the beginning of the experiment is noted. Air is supplied to the flask from the blower at the rate of 1.2 to 1.5 liters per minute after having been first passed through calcium chloride. The test is conducted for 5 hours, after which the oil is cooled to room temperature and weighed. Oil volatility, as a percentage, is determined by the formula:

$$\frac{A - B}{A - C} \times 100,$$

where A is the weight of the flask with oil, before evaporation, in grams;  
 B is the weight of the flask with oil, after evaporation, in grams  
 C is the weight of the flask empty, in grams.

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New methods for studying the properties of gas turbine engine lubricating oils can only be used after it has been determined to what extent the results obtained from them agree with the behavior of the oils in an engine.

In order to check the new methods and to establish close agreement between the results obtained and any variations in the properties of oils used operationally, special control tests are carried out on already known oils.

Laboratory testing methods cannot fully reproduce the behavior of oils under operational conditions. Accordingly, the ultimate serviceability of gas turbine engine lubricating oils is assessed on the basis of results of tests on individual frictional assembly installations of engines and on full-scale engines. In certain cases, oils are tested under in-flight conditions.

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